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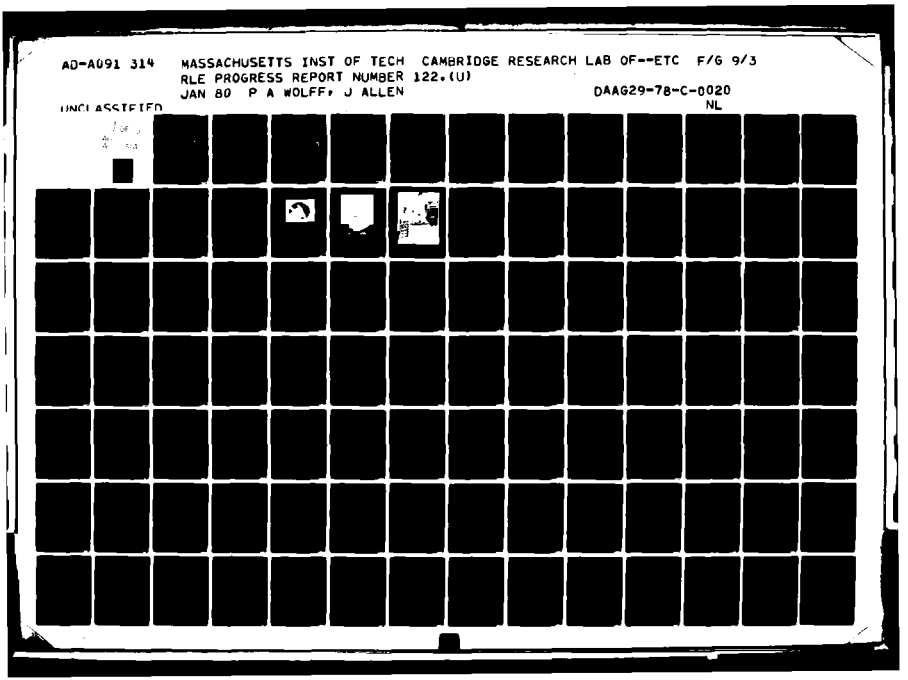

RLE PROGRESS REPORT

No. 122

JANUARY 1980

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
RESEARCH LABORATORY OF ELECTRONICS
CAMBRIDGE, MASSACHUSETTS 02139

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This report, No. 122 in a series of progress reports issued by the M.I.T. Research Laboratory of Electronics, reviews the research progress and states the research objectives of the laboratory for the year ending December 31, 1979. The source of support is indicated for each project.

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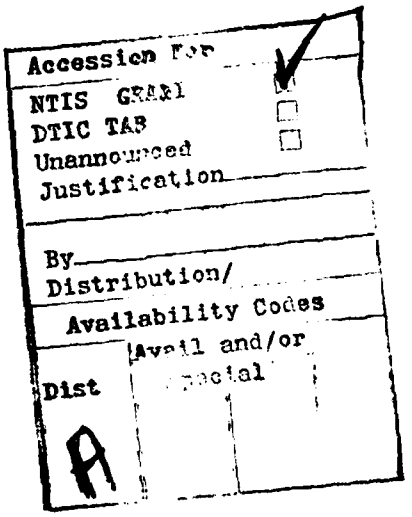
J. Allen

FOREWORD

This report, No. 122 in a series of Progress Reports issued by the Research Laboratory of Electronics, contains the customary annual statement of research objectives and summary of research for each group. The report covers the period January 1, 1979-December 31, 1979, and the source of support is indicated for each project. On the masthead of each section are listed the academic and research staff and the graduate students who participated in the work of the group during the year. The listing of personnel in the back of the book includes only members of the laboratory during 1979.



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GENERAL PHYSICS

I. MOLECULE MICROSCOPY

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Prof. J.G. King
Dr. A. Essig
Dr. J.A. Jarrell
Dr. S.J. Rosenthal
D.J. Ely

Graduate Students

S.N. Goldhaber
C.R. Perley
A.M. Razdow
J.G. Yorker

1. SCANNING DESORPTION MOLECULE MICROSCOPY

National Institutes of Health (Grant 1 R01 GM23678-02)

Jeffrey G. Yorker, John G. King

The purpose of SDMM is to study the spatial variations in the adsorption characteristics of various small molecules on biological surfaces. These characteristics include the density of binding sites for molecules on the surfaces and the binding energy at these sites. By using different molecules, one can infer the local composition of a surface. The energies involved in adsorption and desorption are small, making SDMM a useful tool for nondestructive probing of biological surfaces in vacuum.

In our experiments, the sample is held at an appropriate low temperature and coated with a layer of molecules from a molecular beam. Molecules are then thermally desorbed from the samples with spatial resolution by an array of controlled microheaters on which the sample rests. The desorbed molecules are ionized by electron bombardment, filtered according to mass by an RF quadrupole mass filter, and amplified by an electron multiplier.

During 1979 we completed a prototype microheater array, or thermal desorption array (TDA). The TDA is an 8 x 8 array of 64 10-square micron npn transistors fabricated in the M.I.T. Microelectronics Laboratory. Preliminary tests show that we can melt spots of ice on the TDA surface as desired, and that the thermal time constants are in the right range ($\sim 10^{-4}$ sec). We have also completed a suitable vacuum system with a liquid nitrogen trap that surrounds the detector and reduces water background at mass 18 by a factor of 30. We have also developed a novel

differentially pumped vacuum lock for moving the sample in and out of the high vacuum region without admitting air. This device consists of a large, flat stainless-steel plate which slides over a series of three concentric circular vacuum locks separated by teflon vacuum seals.

We are now starting tests of the entire system, the results of which will guide the design of a refined TDA with 10^4 1-μ elements to be developed elsewhere. Such a device, the analog of a glass slide for an optical microscope or a grid for an electron microscope, will make useful application of the SDMM possible.

Mr. R. Fastow (Course VIII senior), working in the new integrated Circuit Facility, has constructed a new TDA. It consists of blocks of chromium 2 μm on a side and 0.5 μm thick on a silicon wafer which is etched to 0.2 μm in the sample region. The chromium blocks are heated separately in sequence by a focused electron beam, and the heat conducted through the silicon produces desorption from the sample. This method appears to be best adapted to obtaining high spatial resolution.

2. CELL-SURFACE STUDIES

Health Sciences Fund
National Institutes of Health (Grant 1 R01 GM23678-02)

Douglas J. Ely, John G. King

New sample holders consisting of 10 evaporated chromium thin-film heaters on a ground Vycor microscope slide have been constructed, and desorption of water from them observed. Recording equipment has been assembled, and both cell-desorption studies and computation of a catalog of stain and surface combinations can now be resumed with much greater efficiency.

3. SCANNING MICROPIPETTE MOLECULE MICROSCOPE

Health Sciences Fund

Joseph A. Jarrell, John G. King

The instrument has been modified to permit the detection of labelled water by the addition of an in-line uranium reduction furnace. Resolution has been demonstrated to be better than 3 μm with a 2-μm probe tip, and with a 5-μm probe tip

concentration differences of deuterated water of 0.1% can be detected with a signal-to-noise ratio of ∿10 and a time constant of ∿1 sec.

The instrument is currently being applied, in collaboration with Drs. John Mills and Alex Leaf at Massachusetts General Hospital, to the study of transepithelial water fluxes across frog skin sweat glands and toad urinary bladder, respectively, and model tissues for the study of cystic fibrosis and kidney function.

4. PATHWAYS OF TRANSEPITHELIAL WATER FLOW

National Institutes of Health (Grant 1 R01 AM25535-01)

Stanley J. Rosenthal, John G. King, Alvin Essig

Our collaborative project with Dr. A. Essig of the Department of Physiology at Boston University Medical Center began with the development of the molecule flux apparatus which made possible simultaneous measurement of CO_2 production and O_2 uptake without spatial resolution. After obtaining some preliminary results this crude apparatus (built from discarded apparatus) was shelved in favor of another SMMM not unlike that mentioned above (section 3) to be developed and applied to problems of water flow in tissue.

Despite intensive study, disagreement persists concerning the pathways of transepithelial water flow. This problem will be approached by use of mass spectrometry, adapted to provide spatial resolution. The high sensitivity provided by this technique should permit sampling of the concentration profile of water tracer in the "unstirred" layer adjacent to an epithelial membrane, allowing evaluation of the relative magnitude of transjunctional and transcellular water flux at the lumenal surface.

"High-impedance" probes will be prepared from micropipettes of 2-μm outer diameter, plugged with dimethyl silicone to permit diffusive flow of water into the vacuum chamber of a mass spectrometer without tissue damage. The application of H_2O^{18} to the "serosal" surface of a membrane will establish a concentration profile of tracer water at the "lumenal" surface, conforming to the pathways of transmembrane water flow. Initial studies employing Nuclepore, synthetic membranes with well-characterized pore size, will define the degree of spatial resolution available and

optimal operating conditions. Subsequent experiments will be carried out in Necturus gall bladder, a well-studied loose epithelium with large cells and other desirable characteristics facilitating its study. Studies will be done in the presence and absence of isotonic fluid transport, during inward and outward osmotic flow, and in the presence of various agents influencing water transport.

II. DEVELOPMENTAL ELECTRON OPTICS LABORATORY

Academic and Research Staff

Dr. J.W. Coleman

1. THE AUGER ELECTRON MICROSCOPE

Joint Services Electronics Program (Contract DAAG29-78-C-0020)
National Institutes of Health (Grant 1 R01 GM23597)

John W. Coleman

The Auger Electron Microscope has yielded Auger + secondary dark-field images of carbon on tungsten, with spatial resolutions of $\sim$0.8 μ and energy resolution of <20 eV. A typical AEM micrograph is shown in Fig. II-1. The main limitations at present to better resolution of either type are

1. the lack of a facility for alignment of the optical column elements while images are being observed;
2. the influence of slowly varying residual stray fields; and
3. the lack of highly regulated power supplies.

The total electron-optics package (minus the chevron electron multiplier array used as output) is shown in Fig. II-2, and the overall instrument is seen in Fig. II-3.

With the elimination of the problems listed above, the instrument should converge on its theoretical performance level, whereby eventually we expect spatial resolutions of a few angstroms and energy resolutions of a few eV to be demonstrated.

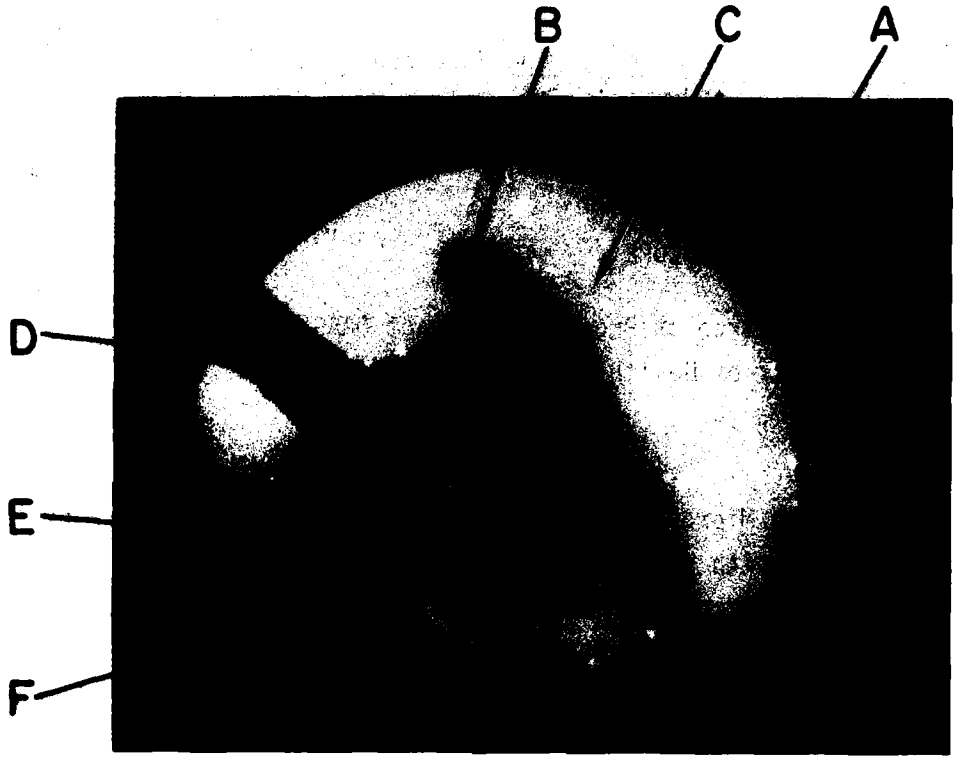

Fig. II-1. AEM micrograph of butt end of 3-mil diam tungsten wire which has been rubbed on graphite. (Low-mag image (330X) taken with Polaroid camera directly from Chevron Electron Multiplier Array phosphor screen, as seen through vacuum window (see Fig. II-3). The CEMA current gain is 1.5×10^6.) The parts of the figure are as follows:

A — Periphery of CEMA phosphor screen
B — A CEMA defect (burnout point)
C — Scattered electrons of no interest (eventually to be apertured out when alignment permits)
D — Support portion of L-shaped tungsten wire, seen as shadow image
E — Dark-field background due to on-axis portion of tungsten wire
F — Auger + secondary image of carbon embedment.

It should be noted that the butt end or specimen end of the wire is pointing away from the phosphor screen, and that the primary dark-field image appears between the specimen end of the wire and the phosphor screen. The situation is analogous to seeing a person's face against the background of the back of his head, and is a consequence of the mirror optics necessary for a high-efficiency collection of Auger electrons.

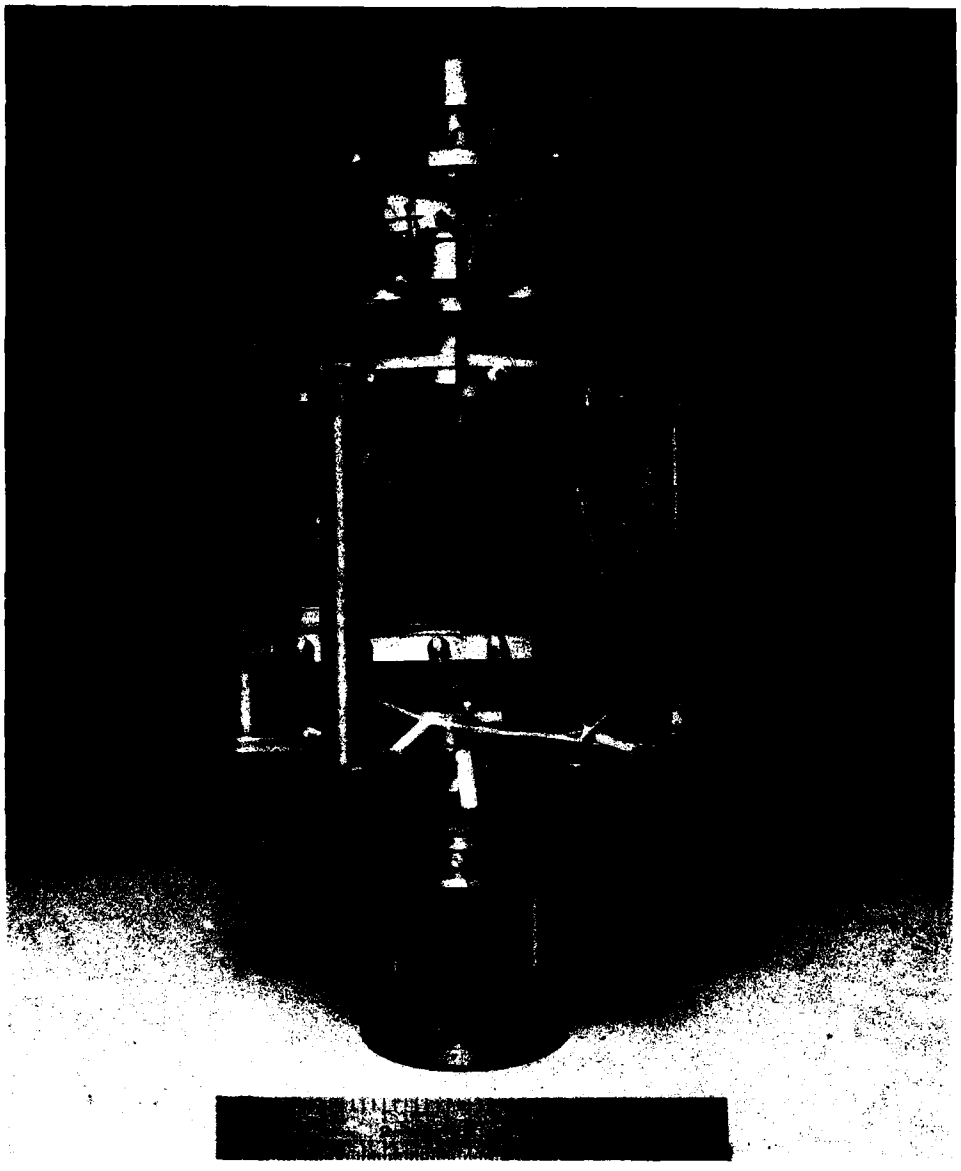

Fig. II-2. AEM electron-optics package.
A — Electron gun for excitation of Augers in specimen
B — Auger mirror-objective lens
C — Specimen-holder drawer
D — Accelerator
E — Set-up lens for energy analyzer
F — Deflector ring
G — Spherical-aberration-corrector foil
H — Magnetic-prism winding assembly
I — Analyzer-mirror cathode
J — Magnetic prism
K — Energy-analyzer assembly
L — Projector-discriminator
M — Deflector ring and stigmator
N — Projector #2
O — Deflector ring
P — Projector #3.

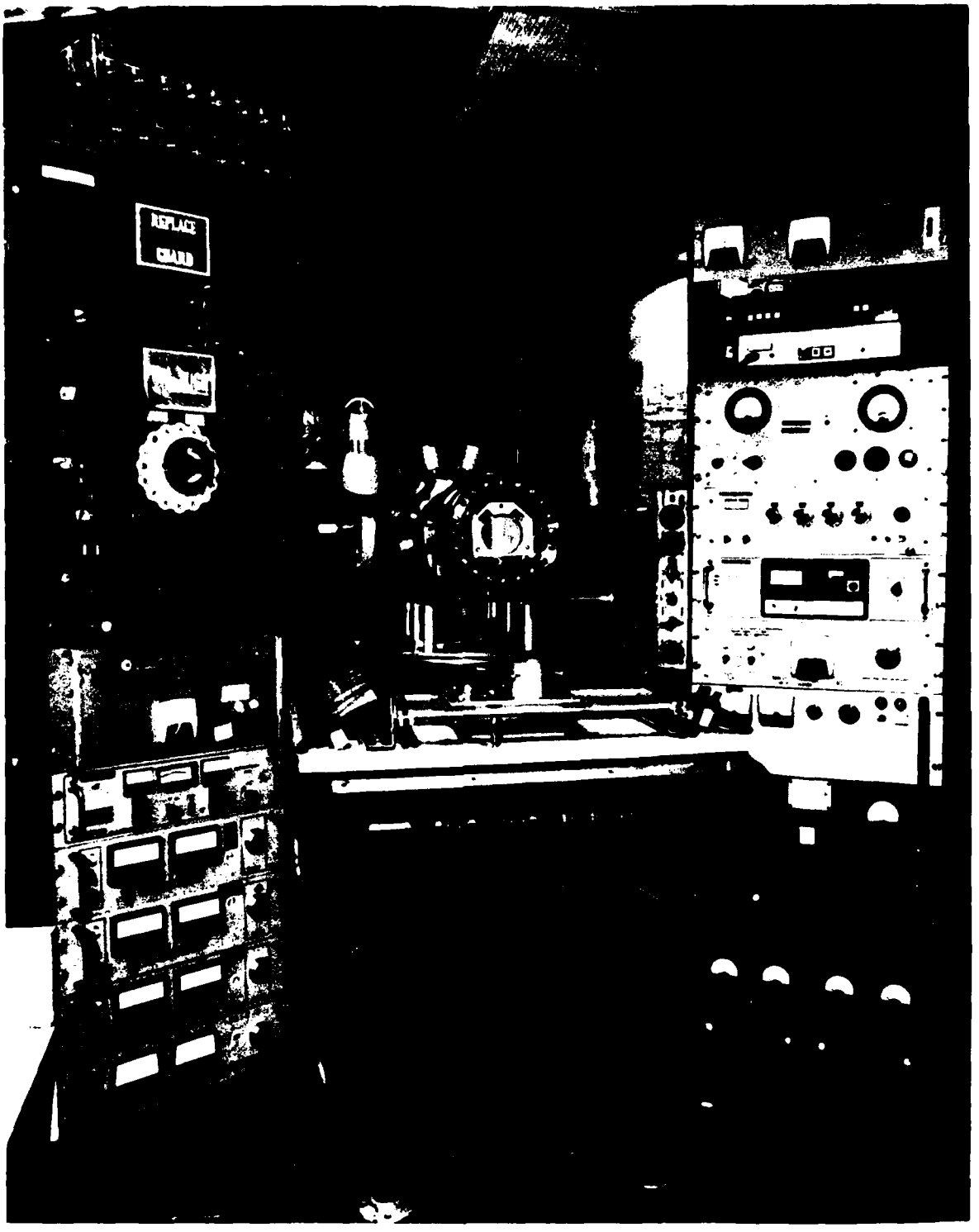

Fig. II-3.

III. SEMICONDUCTOR SURFACE STUDIES

Academic and Research Staff

Prof. J.D. Joannopoulos
Dr. R.B. Laughlin
Dr. Y-M. Wang

Graduate Students

E.M. Kunoff
D-H. T. Lee
W.R. Pollard

1. EXCITATIONS AT SURFACES AND INTERFACES OF SOLIDS

Joint Services Electronics Program (Contract DAAG29-78-C-0020)

John D. Joannopoulos, Yi-Ming Wang, D-H. Tom Lee

We have developed techniques which allow us to calculate the elementary excitations of crystalline surfaces exactly within a localized orbital approach. This approach provides an attractive and physical real-space description of the states of the system.

Specifically, we have developed a microscopic theory of Fermi-level pinning and Schottky-barrier formation in metal-semiconductor junctions for submonolayer and monolayer metal surfaces. The theory explains how the Schottky barrier can be formed at such low coverage and describes novel exchange reactions at the surface of the semiconductor.

In addition, we have studied the effects of cleavage steps at surfaces and find a very strong correlation between the density of such steps and the unusual band-bending behavior that is observed experimentally depending on the nature of the surface.

We are currently investigating the electronic states at wurtzite surfaces and the effects of core-excitons on surface-state properties.

(III. SEMICONDUCTOR SURFACE STUDIES)

2. SURFACE AND DEFECT EXCITATIONS IN COVALENTLY BONDED SOLIDS

U.S. Navy — Office of Naval Research (Contract N00014-77-C-0132)

John D. Joannopoulos, Robert B. Laughlin, Estelle M. Kunoff

We have developed a theoretical formalism that will enable us to study the electronic states at disordered Si-SiO_2 interfaces. In particular, we have concentrated on developing a realistic tight-binding model to describe accurately the electronic states and wave functions in bulk crystalline and amorphous SiO_2. We find that most of the features of SiO_2 are insensitive to topology and are thus universal among all allotropes in which the integrity of the SiO_4 tetrahedron is preserved. A remarkable effect of this universality is a dipole selection rule forbidding the first optical transitions. We are currently investigating the properties of Si-SiO_2 interfaces.

IV. PHOTOEMISSION SPECTROSCOPY

Academic Research Staff

Prof. F.R. McFeely

Graduate Students

M.R. McClellan
M.J. Sayers
N.D. Shinn
M. Trenary

1. INVESTIGATIONS OF MOLECULAR CHEMISORPTION ON SEMICONDUCTORS BY ANGLE-RESOLVED PHOTOEMISSION SPECTROSCOPY

Joint Services Electronics Program (Contract DAAG29-78-C-0020)

F. Read McFeely, Michael R. McClellan, Michael J. Sayers, Michael Trenary, Neal D. Shinn

During the past year this project has progressed from the stage of instrument development to a fully operational experimental effort. The first experiment undertaken with our spectrometer was a study of the chemisorption site geometry for CO bound to ZnO $10\bar{1}0$ surfaces.

Despite the importance of molecular chemisorption processes in modifying surface electronic properties, and in participating in reactions both with the surface (e.g., etching) and on the surface (e.g., catalytic reactions), studies of the fundamental nature of molecular bonding to the surfaces of these materials have lagged far behind corresponding efforts to understand chemisorption on metals.

In many respects, this system is an extremely attractive one to study. Zinc oxide serves as a practical catalyst for the synthesis of methanol from CO and H_2, and the CO-ZnO system has served as a prototype for the study of surface photooxidation reactions. A detailed mechanistic understanding of both of these important processes clearly requires a knowledge of the bonding mechanism of CO to the surface. In addition, the intrinsic surfaces of ZnO (the nonpolar $(10\bar{1}0)$ and $(11\bar{2}0)$; and the polar (0001) and $(000\bar{1})$ faces) have been very well characterized by LEED. These results demonstrate that the surface is substantially unreconstructed, with the $(10\bar{1}0)$ surface, in particular, also exhibiting a (1x1) unit mesh with $\sim$0.5 Å zinc ion displacements from their ideal positions. Thus our information on molecular

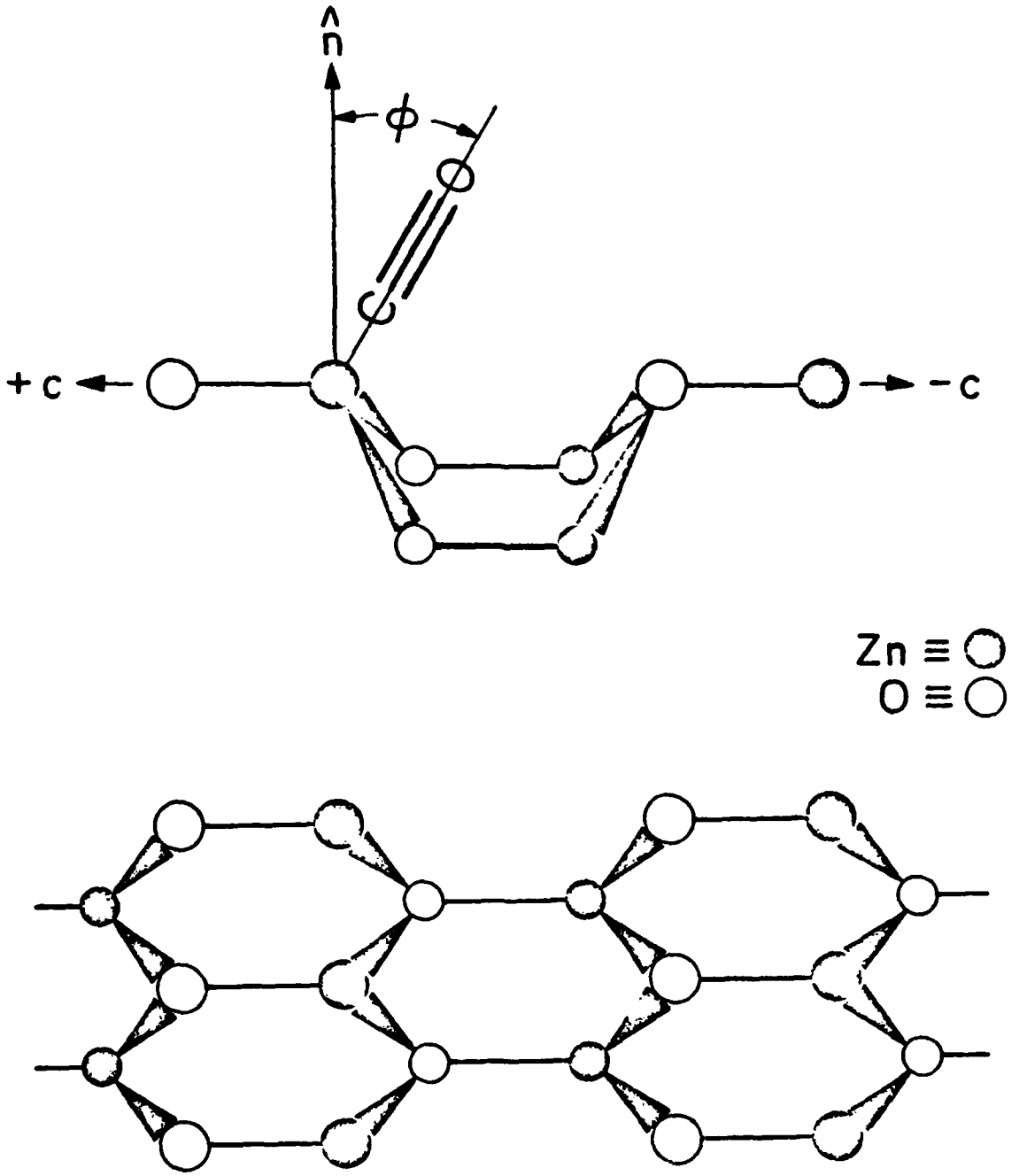

Fig. IV-1.

orientation can be related to a surface geometry which is both simple and accurately known. In addition, extensive angle-integrated photoemission studies of CO chemisorption on ZnO by Solomon and co-workers (with whom we collaborated on this project), performed at the Lincoln Laboratory, had elucidated the thermodynamics of the adsorption process and methods of crystal preparation, which greatly facilitated this work.

Our results, shown in Fig. IV-1, indicated that the carbon monoxide is bound to the surface zinc atom, by means of a dative bond from the CO 5 σ molecular orbital. The molecules were found to be oriented at an angle of $\phi \gtrsim 30°$ from the surface. As the position of the "missing" oxygen atom on this surface would be $\phi = 19°$, the carbon monoxide molecule is thus acting as a substitute ligand. However, since the CO-Zn bond is rather weak, the molecule is bent from 19° to 30° as a result of an electrostatic interaction with the rest of the surface, particularly the nearest oxygen atom.

Current work involves extending this study to other crystal faces of ZnO, particularly the polar faces where bonding to defects may be important. During the coming year we will be extending studies of this type to the less ionic groups IV and III-V surfaces.

2. STUDIES OF SEMICONDUCTOR SURFACE REACTIVITY

Michael R. McClellan, Neal D. Shinn, F. Read McFeely

Preparations have been made during the past year for experiments studying the surface chemistry of semiconductor etching processes (e.g., plasma etching). A combination of photoemission and electron-energy-loss spectroscopy will be used for this purpose.

V. ATOMIC RESONANCE AND SCATTERING

Academic and Research Staff

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A.L. Migdall
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W.P. Moskowitz
T.P. Scott
J.A. Serri
D.A. Smith
N. Smith
W.P. Spencer
A.G. Vaidyanathan
R.E. Walkup
G.R. Welch

1. STUDIES OF ROTATIONAL ENERGY TRANSFER

U.S. Air Force — Office of Scientific Research (Grant AFOSR-76-2972)

Timothy A. Brunner, Marie Durand, David E. Pritchard,
Thomas P. Scott, Neil Smith

The most probable type of inelastic collision involving molecules is Rotational Energy Transfer (RET), an important process in high-power gas lasers and interstellar clouds. We have measured rate constants for the RET process

$$Na_2^*(j_o) + X \rightarrow Na_2^*(j_o+\Delta) + X - \Delta E_r, \qquad (1)$$

where the * indicates that the Na_2 is in an electronically excited state, X is the target atom, j_o is the initial rotational quantum number, Δ is the change in rotational quantum number, and ΔE_r is the increase in rotational energy.

Since at typical temperatures roughly 100 rotational levels are populated, there are thousands of rate constants, $k(j_o \rightarrow j_o+\Delta)$, needed to characterize the system. Use

*Assistant Professor at Wellesley College.
+Visiting Scientist from Observatoire de Paris, France.

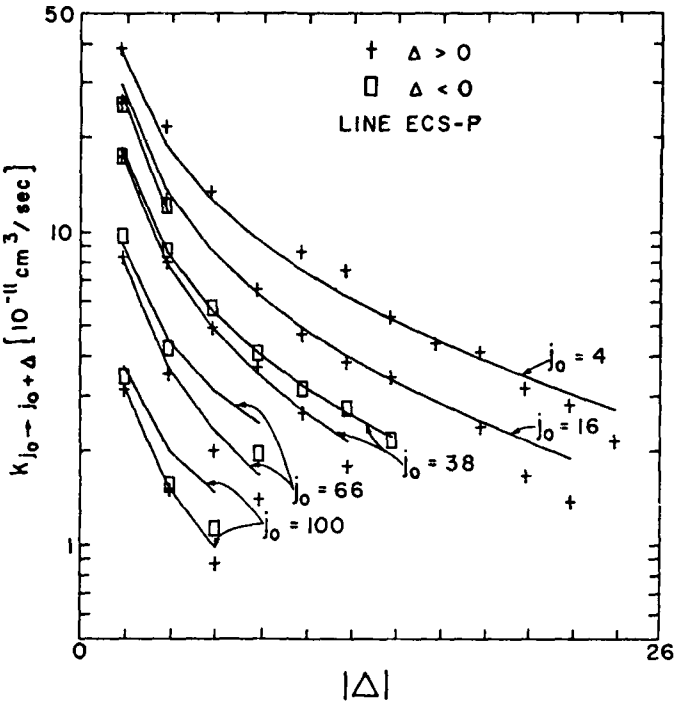

Fig. V-1. Measured Na_2^*-Xe rate constants, $k(j_0 \to j_0+\Delta)$, versus $|\Delta|$ for j_0 = 4, 16, 38, 66, 100. The lines connect points generated by the ECS-P fit.

of a computerized data-acquisition system and data-analysis programs have made possible accurate measurements of typically 50 to 100 level-to-level RET rate constants with j_0 ranging from 4 to 100 and $|\Delta| < 28$ for each of eight target gases: X = He, Ne, Ar, Kr, Xe, H_2, N_2, and CH_4. Figure V-1 illustrates the (apparently) complex dependence of the rate constants on j_0, $|\Delta|$, and the sign of Δ.

This unprecedented wealth of accurate data has made it possible for us to search systematically for fitting laws[1] — laws which express the hundreds of rate constants in terms of a few physically significant parameters. We have found a highly successful fitting law which combines the theoretically predicted Energy Corrected Sudden (ECS) scaling law with our empirically discovered[2] Power (P) law. The resulting fitting law, ECS-P, can fit 100 experimental rate constants with only 3 variable

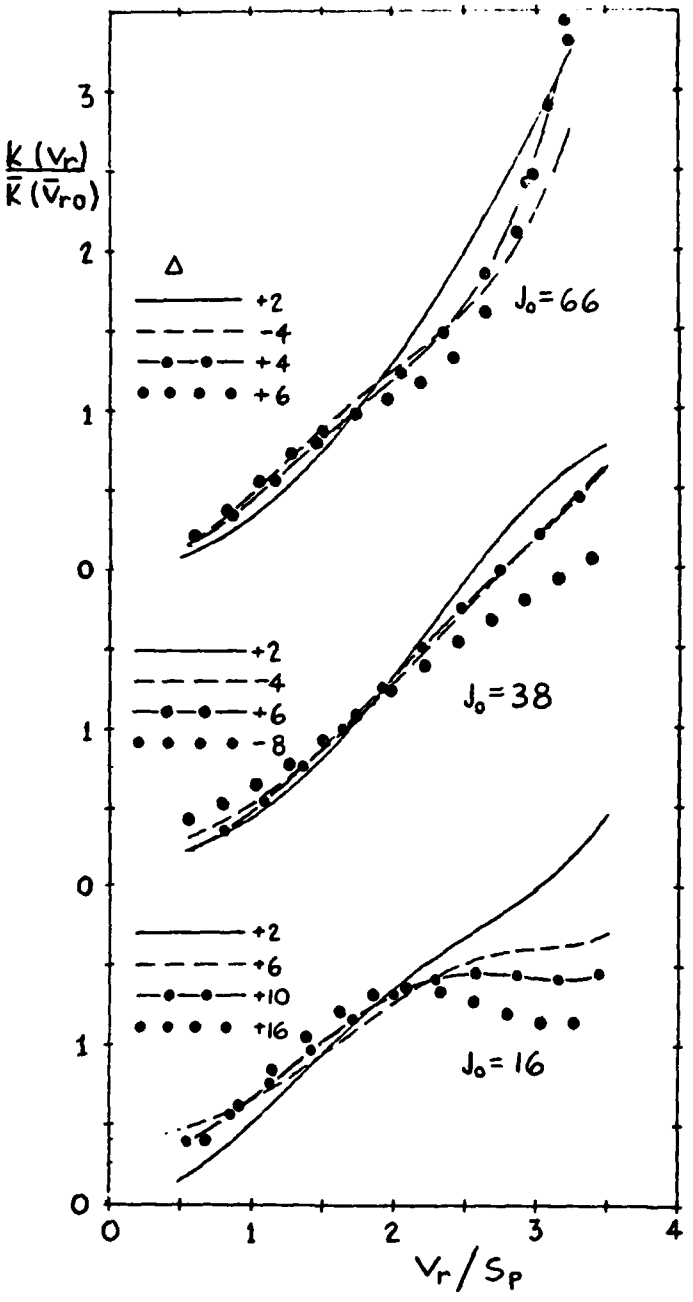

Fig. V-2. The normalized rate constants plotted versus the relative velocity v_r in units of a thermal velocity s_p.

parameters[3] to within our experimental error of ≃10%. In Fig. V-1 the ECS-P fit to the data, represented by the solid lines, reproduces the "complex" dependence of the rate constants on j_0 and Δ. A comprehensive set of fits to various fitting laws of both our measurements and other accurate data has demonstrated the wide applicability of ECS-P.[4]

We have recently demonstrated[5] a new technique to measure the velocity dependence of the rate constants of process (1) which takes advantage of the Doppler effect. By simply tuning the laser, we can vary the mean-square collisional velocity (temperature) by more than an order of magnitude because when the laser is exactly tuned to line center it excites slow molecules, but when it is tuned slightly off-resonance, then only fast molecules are Doppler-shifted into resonance.

The results of our measurements for Na_2^* colliding with Xe are shown in Fig. V-2 where the normalized rate constant is plotted versus the relative velocity v_r in units of a thermal velocity s_p. The $j_0 = 38$ data rise rather linearly with increasing velocity, indicating that the cross sections are fairly independent of velocity. For $j_0 = 66$ the rates rise faster than linearly so the cross sections are rising with increasing velocity. These results seem to confirm the naive notion that the faster the molecules collide the more RET will take place. Surprisingly, the $j_0 = 16$ rates actually fall off with increasing velocity, more so for the larger changes in angular momentum Δ. A possible explanation for this surprising behavior is that the long-range attractive intermolecular potential can suck slow-moving atoms in to undergo "hard" collisions more easily than fast atoms.

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2. LEVEL-TO-LEVEL ENERGY-TRANSFER DIFFERENTIAL CROSS SECTIONS USING DOPPLER VELOCITY ANALYSIS

National Science Foundation (Grant CHE79-02967)

John A. Serri, Alejandro Morales-Mori, Warren P. Moskowitz,
David E. Pritchard, Christopher H. Becker, James L. Kinsey
[James L. Kinsey is Professor in the Department of Chemistry, M.I.T.]

We have recently measured differential cross sections for rotational level-changing collisions in ground-state Na_2 with Ar[1]:

$$Na_2\ (v''=0,\ j_i=7) + Ar \rightarrow Na_2\ (v''=0,\ j_f) + Ar.$$

Measurements range in $\Delta j(j_f-j_i)$ from -4 to 80 and in θ from 0 to π.

The experiment is performed in a new differentially pumped crossed-beams apparatus capable of producing intense molecular beams with narrow velocity spreads ($\sim$10% FWHM) and internal temperature (typically 50°K). The Ar and Na_2 intersect at 90°. Two cw dye lasers make the level-to-level measurements: one laser (called the pump) modulates by optical-pumping the initial level population ($v''=0$, j_i); the other laser (called the analysis) measures the angular distribution of the final level ($v''=0$, j_f) using the ADDS method in which the angle of scattering is inferred from the Doppler shift.[2,3] Level-to-level scattering signals are isolated by phase-detecting the fluorescence from ($v''=0$, j_f) at the pump-modulation frequency.

Level-to-level cross sections, $\sigma_{i\rightarrow j}(\theta)$, are shown in Fig.V-3. All cross sections display a steep rise from zero to a maximum with a gradual decrease at larger angles. This maximum follows the empirical relation $1.4\ \Delta j + 20$. The scattering is dominated by the repulsive core of the intermolecular Na_2-Ar potential. Our observations can be qualitatively understood classically as follows: For a given molecular orientation and impact parameter there is an associated Δj and θ. When the impact parameter is small, the repulsive force is large, producing a large deflection θ and large integrated torque (i.e., Δj). As the impact parameter increases, the force decreases and so must θ and Δj. The maximum in $\sigma(\theta)$ for a particular Δj arises because there is, for a particular Δj, a minimum deflection angle with respect to orientation, and all orientations near this one give roughly the same deflection,

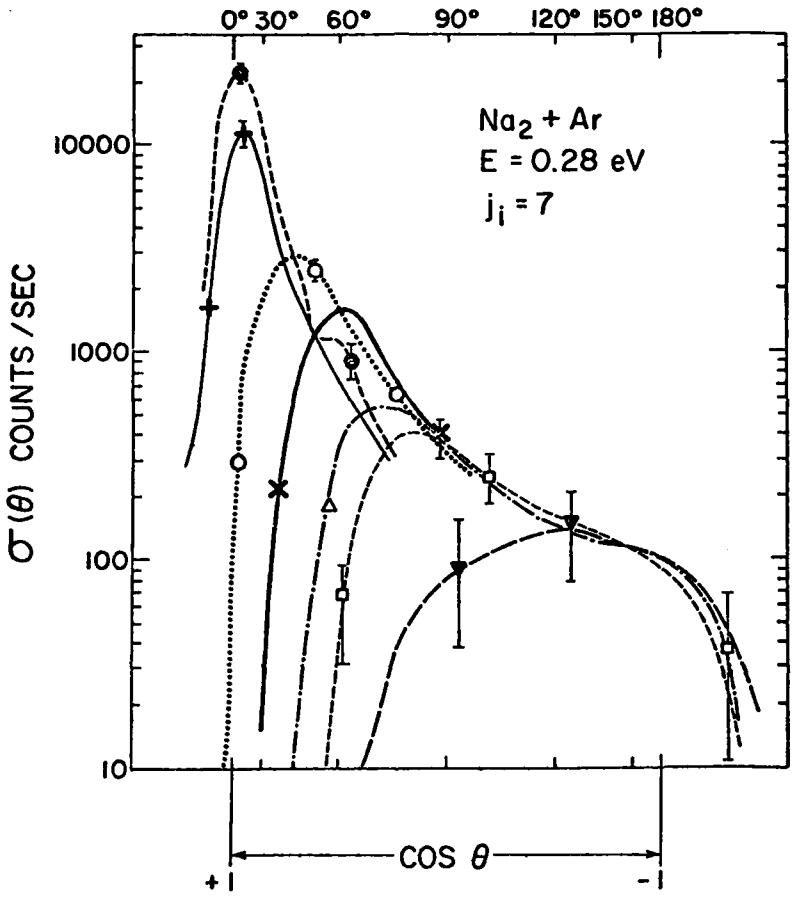

Fig. V-3. The level-to-level cross sections $\sigma_{j\to f}(\theta)$ for $j_i = 7$ are given in counts/sec vs θ (upper x-axis) and vs frequency offset or cos θ (lower x-axis). Each $\sigma(\theta)$ from 0 to π consists of approximately 40 data points; typical points with their error bars are shown. The existence of signal outside the nominal $0 < \theta < \pi$ range is due to imperfect resolution.

Legend: • $\Delta j = 2$; + $\Delta j = -4$; o $\Delta j = 16$; x $\Delta j = 28$; Δ $\Delta j = 40$; □ $\Delta j = 48$; ▼ $\Delta j = 80$.

causing the maximum. We call this phenomenon a "halo" in analogy to the atmospheric optical phenomenon.

We plan to extend the present measurements to more initial levels and to different collision energies. Trends in the data will provide insight into the collision process, and the data itself should provide a sound basis for tests on different potential surfaces and current approximation methods used for calculating inelastic differential cross sections. The same experimental method can be extended to vibrational-energy transfer. Preliminary measurements will soon be under way.

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3. MOLECULAR SPECTROSCOPY

National Science Foundation (Grant PHY79-09743)

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The van der Waals group has been involved in laser spectroscopic studies of alkali-rare gas diatomics formed in a supersonic molecular beam. These weakly bound molecules ($D_{eX} \sim 1$ meV) are interesting theoretically and experimentally. Special conditions are necessary to produce the molecules (supersonic beam), and the potential energy surfaces extracted from the data serve as a check for theoretical calculations[1] and provide insight into interpretation of line broadening[2] and scattering experiments.[3]

Earlier work[4] done on NaNe has been expanded to include analysis of the $B^2\Sigma^+$ state. A more definitive vibrational assignment of the $A^2\Pi_r$ - $X^2\Sigma^+$ manifold has been developed using long-range theories.[5,6] A deperturbation analysis which

involves fitting the data to a model Hamiltonian and calculating RKR potentials, and then deducing Franck Condon factors is in progress.[7]

Laser excitation of NaAr formed in a beam has yielded $A^2\Pi_r$ - $X^2\Sigma^+(v,o)$ for 10 < v < dissociation, and several $B^2\Sigma^+$ - $X^2\Sigma^+$ bands. Analysis and application of long-range theories corroborates work done elsewhere[8] and provides new information on both the $A^2\Pi_r$ and $B^2\Sigma^+$ states.

Currently, using two photons of different energy, we are searching for a Rydberg state in NaAr which correlates to $Na(5^2S)$ + $Ne(^1S)$ in the separated atom limit. These states have potentials of theoretical interest but have never been observed before.

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VI. INTERFACIAL CHEMISTRY

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1. PHOTOACOUSTIC SPECTROSCOPY AND CHEMICALLY MODIFIED SURFACES

Joint Services Electronics Program (Contract DAAG29-78-C-0020)
National Science Foundation (Grant DMR-78-24185)

Ralph H. Staley, Manfred M. Kappes, John B. Kinney

Work has focused on using photoacoustic spectroscopy (PAS) to characterize the results of chemical attachment reactions of molecules to surfaces and to study heterogeneous catalyst systems and their reactions. Electronic spectra in the UV-visible and overtone bands in the near-IR have been utilized in these studies. We have also recently begun using photoacoustic detection with a Nicolet 7199 FTIR system to obtain spectra in the mid-infrared range. All samples were run using a cell built in our laboratories that allows control of the gas composition in contact with the sample. The sample chamber can be sealed and detached, so that samples can be loaded in a dry box. Temperature control of the sample stage is also possible.

Ferrocene-centered reagents can be bound to the surface of high-surface-area (400 m^2/g) silica powders by reaction of the silica with solutions of (1,1'-ferrocenediyl) dimethylsilane (DMP), or related reagents. PAS reveals a band-position shift from the unreacted reagent to the reacted product indicating ring opening of the strained C-Si-C linkage bridging the two cyclopentadienyl rings to yield a simple, monosubstituted ferrocene center attached to the surface. Reversible oxidation of the surface-bound ferrocene centers to ferricenium centers by washing with acidic solutions of benzoquinone is confirmed by photoacoustic spectra. The surface-confined ferricenium can be used to oxidize N,N,N',N'-tetramethyl-p-phenylenediamine

(TMPD) to $TMPD^{+\cdot}$ in solution; this reaction allows an estimate of the surface coverage. This, in turn, provides a means to calibrate PAS signal response to surface for the powder used.

Similar use of PAS has been employed to monitor attachment chemistry using $SiCl_4$ with organic dyes on powders, flat surfaces, and silica microstructures. For this work, quantification of PAS signal response to surface coverage is obtained by comparing transmission and photoacoustic spectra for suitable samples. Photoacoustic spectra, however, can be conveniently obtained for a wider range of coverages and for coverages of nonuniform substrates such as microstructures.

The utility of PAS for investigations of heterogeneous catalyst systems is illustrated by a study of reactions of molybdenum hexacarbonyl, $Mo(CO)_6$, on various support materials. On silica at -50°C, radiation-induced production of $Mo(CO)_5$ on the surface can be followed. With further irradiation, more highly coordinately unsaturated molybdenum species are generated. The effects of support composition and preparation on these reactions have also been investigated in this study using PAS.

PAS can be used in the near-IR to examine vibrational overtone and combination bands. Silica samples derivatized with ferrocene using DMP illustrate the utility of this region. The DMP-derivatized silica shows both an aliphatic C,H-band at 1.7. μ and an aromatic C,H-band at 1.63 μ.

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VII. X-RAY DIFFUSE SCATTERING

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Joint Services Electronics Program (Contract DAAG29-78-C-0020)

Robert J. Birgeneau

This research program centers around a two-spectrometer x-ray diffuse-scattering system based on a Rigaku 12-kW rotating-anode x-ray generator. The apparatus is designed in such a way that one may easily tailor the instrumental resolution function to optimize studies of structure and fluctuations in a vast range of physical systems. Angular resolution of 1.8 seconds of arc and sample temperature control of 2 mK between 10 K and 500 K are available. We are currently implementing a position-sensitive detection system to allow rapid scans over a wide range of scattering angles, again with continuously variable resolution. Our current research program emphasizes structure and melting transitions both for monolayer physiadsorbed films on graphite and for layered liquid crystals. The surface experiments involve in situ high-precision vapor-pressure and surface-coverage measurements. Experiments are also performed using the x-ray synchrotron facilities at D.E.S.Y. (Hamburg, Germany) and S.L.A.C. (Stanford). We are currently designing a two-spectrometer high-resolution x-ray system to be permanently located at the National Synchrotron Light Source under construction at Brookhaven National Laboratory.

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*Visiting Professor from Harvard University; now returned.

(VII. X-RAY DIFFUSE SCATTERING)

1. COMMENSURATE-INCOMMENSURATE TRANSITION OF MONOLAYER KRYPTON ON GRAPHITE

We have carried out an x-ray scattering of the commensurate-incommensurate transitions (C.-I.T.) of monolayer krypton on the surface of ZXY exfoliated graphite at temperatures of 80.0 K and 89.3 K. At submonolayer densities the krypton has a $\sqrt{3}$ x $\sqrt{3}$ R 30° structure, commensurate with the graphite (0001) plane. As a function of chemical potential, and hence coverage, the krypton atoms move out of the $\sqrt{3}$ x $\sqrt{3}$ R 30° positions, forming a triangular lattice which is incommensurate with the substrate. We find[1] that (a) the transition appears to be second order with the simple power-law behavior $\varepsilon \sim (\mu-\mu_c)^{1/3}$, (b) the transition occurs via the formation of a superlattice of domain walls, and (c) interesting and complicated lineshape phenomena occur near the transition. Current theories of the C.-I.T. are not adequate to describe these results.

2. STRUCTURE, PHASE DIAGRAM AND MELTING OF XENON ON GRAPHITE

The spacing of the xenon atoms in bulk xenon is intermediate between the 2 x 2 and $\sqrt{3}$ x $\sqrt{3}$ structures on graphite. This suggests that xenon might form an incommensurate lattice on graphite. We do indeed find that xenon forms a triangular lattice which is incommensurate except at low temperatures ($T < 65$ K) and high coverages. At higher temperatures where interesting thermodynamic phenomena occur, the system thence functions as a model 2D continuous-symmetry solid. In our x-ray studies we find evidence for (i) the existence of a well-defined triple point as in 3D materials, (ii) a sharp nearly second-order melting transition, and (iii) novel coexistence phenomena at low coverages which indicate the importance of finite-size effects. Our analysis of the triple-point and coexistence experiments is complete and has been submitted for publication.[2] We are currently carrying out a detailed analysis of the melting data in order to make a quantitative comparison with current theories such as that proposed by Kosterlitz and Thouless.

3. STRUCTURE, PHASE DIAGRAM AND TRANSITIONS OF MONOLAYER AND BILAYER MOLECULAR OXYGEN ON GRAPHITE

Oxygen adsorbs onto graphite in the molecular state; the oxygen molecule is unique among homonuclear diatomic species in that it is paramagnetic with spin S = 1. The interplay between the magnetic, orientational, and structural degrees of freedom make both 3d and 2d oxygen rich and quite subtle. Previously, susceptibility and neutron-scattering studies of monolayer and bilayer oxygen on graphite have been performed. Both experiments suggest that oxygen solidifies at about 30 K for a monolayer and 40 K for a bilayer. The neutron studies suggest that the structure is triangular with a nearest neighbor intermolecular spacing close to that in the bulk, and concomitantly, incommensurate with the graphite. The neutron studies also suggest that bilayer oxygen undergoes an antiferromagnetic transition at 11.9 K. We have carried out a detailed x-ray study of the structure of monolayer and bilayer oxygen as a function of coverage from 0.5 to 2.5 monolayers and of temperature from 12 K to 50 K. We find evidence for at least four distinct phases, only two of which are triangular. In particular, the bilayer phase is only triangular within 2 K of melting, in explicit contradiction with the neutron results. We have not yet managed to produce an unambiguous model for the structure, although the data are consistent with incommensurate successive layers. Work on this most interesting system is continuing.

4. STRUCTURE OF WELL-ORDERED SMECTIC PHASES

Smectic liquid crystals are conventionally defined as systems consisting of a one-dimensional density wave in a three-dimensional fluid. However, in many liquid crystals there are additional phases, conventionally labelled, SmB, D, E, F, G, and H with various degrees of order perpendicular to the density-wave direction. Further, existing x-ray evidence seems to indicate that this in-plane order often only extends a limited distance along the one-dimensional axis. As discussed in last year's report, we have constructed a simple model based on the Halperin-Nelson-Kosterlitz-Thouless theory of melting in 2 dimensions which appears to be able to account for the variety of phases suggested by the experiments. Most importantly, we identify

a new 3D phase consisting of "stacked hexatics" – a system with long-range orientational order, but only short-range in-plane and between-plane positional order.[3] We have now carried out a high-resolution x-ray study of the SmB phase of 4.0.8 which, according to existing data, appeared to be describable as the stacked hexatic phase. Unfortunately, our x-ray data show clearly that the SmB phase of 4.0.8 corresponds to an extremely soft solid.[4] It now appears likely that most systems labelled as higher order smectics are, in fact, solids as we have found for 4.0.8. This is rather disappointing since our "stacked hexatic" phase would have represented a genuinely new phase of matter.

5. CRITICAL BEHAVIOR OF THE SmA-SmC TRANSITION OF $\bar{8}$S5

We have carried out measurements of the A-C transition in $\bar{8}$S5 in magnetic fields which are sufficiently large that the liquid-crystal director is held fixed in the SmC phase. Hence the SmA Bragg peak splits into a ring of scattering. The angular breadth of the ring gives the magnitude of the tilt-order parameter ϕ directly. One may also measure simultaneously the planar spacing d. We find to great precision $d_A - d_C \sim \phi^2$ and that ϕ exhibits mean-field behavior, that is, $\phi \sim (T_c - T)^{1/2}$, over the reduced temperature range $5 \times 10^{-3} > 1 - T/T_c > 3 \times 10^{-5}$. We have constructed a straightforward theory using the Ginzburg criterion which indicates that the true critical region should be unobservably small for most A-C transitions; this enables one to understand a large number of hitherto puzzling results in literature. These results have now been published.[5]

6. OBSERVATION OF ALGEBRAIC DECAY OF POSITIONAL ORDER IN A SMECTIC LIQUID CRYSTAL

A smectic-A liquid crystal in three dimensions has been predicted to exhibit algebraic decay of the layer correlations rather than true long-range order. As a consequence, the smectic Bragg peaks are expected to be power-law singularities of the form $q_{\parallel}^{-2+\eta}$ and $q_{\perp}^{-4+2\eta}$, where $\parallel(\perp)$ is along (perpendicular to) the smectic density-wave direction, rather than delta-function peaks. Observation of these phenomena requires very high instrumental resolution together with a resolution

function with wings which drop off much more rapidly than $q_{\parallel}^{-2}(q_{\perp}^{-4})$. We show that these requirements may be met by using a three-crystal x-ray spectrometer with multiple-reflection channel-cut crystals as monochromator and analyzer. We find that the smectic-A Bragg peaks observed in the liquid crystals octyloxycyanobiphenyl are indeed consistent with the predicted power-law singularity form. Furthermore, the explicit values of η required to describe the measured profiles are in accordance with calculations of η using the harmonic approximation with empirically determined splay and layer compressibility elastic constants.[6]

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VIII. QUANTUM ELECTRONICS

A. Laser Applications

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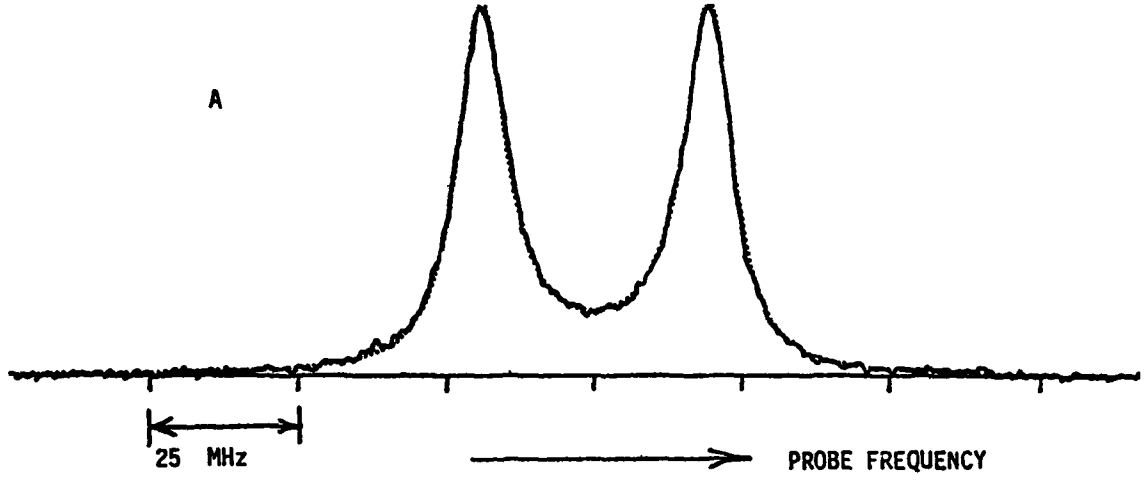
1. HIGH-RESOLUTION STUDIES OF THE AC STARK EFFECT IN AN ATOMIC BEAM AND THE INFLUENCE OF ATOMIC RECOIL

National Science Foundation (Grant PHY79-09739)
Joint Services Electronics Program (Contract DAAG29-78-C-0020)

Philip R. Hemmer, Frederick Y. Wu, Shaoul Ezekiel

We have performed careful measurements of the ac Stark effect in an atomic beam of sodium and have found the influence of atomic recoil to be significant. Such measurements have been of much interest, recently,[1] because they provide important information about the effects of resonance radiation on two-level systems. Previous observations of the ac Stark effect in an atomic beam[2] have been generally qualitative. Our present measurements, however, allow, for the first time, a precise quantitative comparison with theory.

The experiment was performed on an atomic beam of sodium which was prepared as a two-level system by optical pumping techniques.[3] The relevant states are the $3\ ^2S_{1/2}$ ($F=2$, $m_F=2$) and the $3\ ^2P_{3/2}$ ($F=3$, $m_F=3$) hyperfine levels of sodium. Transitions between these states are driven by a near-resonance pumping field which is collimated to give an extended region of uniform intensity. A weak probing field, focused on the driven atoms, induces transitions from $3\ ^2P_{3/2}$ ($F=3$, $m_F=3$) to the $4\ ^2D_{5/2}$ ($F=4$, $m_F=4$) hyperfine levels, and the resulting fluorescence is monitored with a cooled photomultiplier.



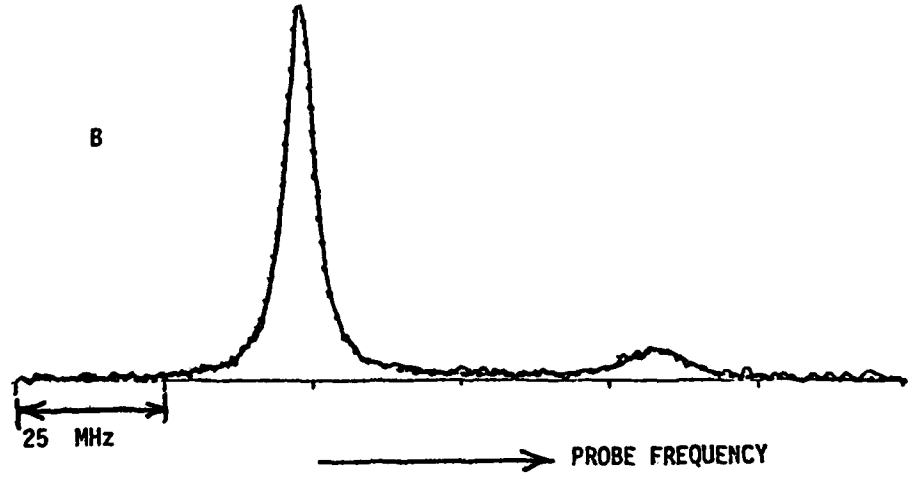


Fig. VIII-1.

The line shapes obtained at low pump intensities resemble, as predicted, Lorentzians with widths approaching the 3.3 MHz width of the 4 $^2D_{5/2}$ (F=4, m_F=4) state. At higher pump intensities, an asymmetry appears in the line shapes, for exactly on resonance pump field, which is not predicted by three-level theory. Symmetry can be restored by cocking the angle between laser and atomic beams slightly away from orthogonal, but at the expense of introducing a broadening. The discrepancies at high pump intensities can be explained by taking into account the many momentum-conserving recoils which must take place as the two-level atoms traverse the extended region of intense, resonant, pumping radiation.

Net atomic recoil[4] occurs whenever an atom absorbs a photon from a unidirectional light beam and, subsequently, spontaneously emits in a random direction. When averaged over an ensemble of atoms, this results in a fixed net increase in velocity in the direction of light propagation, and therefore an apparent negative detuning of the pump-field frequency due to the Doppler effect. Because of the distribution in velocities along the atomic beam there will also be a spread in this apparent negative detuning. If the many recoils as well as the atomic velocity distribution are included in the calculation, excellent agreement between theory and experiment is obtained. Figure VIII-1A shows the probe absorption line shape for an on-resonance, 230 mW/cm^2 pump with laser and atomic beams cocked approximately 2 mrad away from orthogonal. Figure VIII-1B is the line shape for a pump-frequency detuning of -40 MHz away from resonance. The dotted curves in both figures are calculated from theory and include the effects of recoil and the atomic velocity distribution.

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2. FOLDED DOPPLER-BROADENED THREE-LEVEL MOLECULES IN INTENSE MONOCHROMATIC FIELDS: HIGH-RESOLUTION STUDY IN I_2 VAPOR

National Science Foundation (Grant PHY79-09739)
Joint Services Electronics Program (Contract DAAG29-78-C-0020)

Robert E. Tench, Richard P. Hackel, John E. Thomas, Shaoul Ezekiel

We have performed very high resolution studies of Doppler-free resonances in folded three-level systems of I_2 vapor subject to intense monochromatic fields. Line shapes have been obtained for saturation parameters (I/I_{sat}) up to 10^4.

Detailed studies of the interaction of intense monochromatic fields with two- and three-level systems[1] provide important tests of theoretical predictions and also are essential to a complete understanding of powerful new spectroscopic techniques. In comparing experimental line shapes for ultrahigh intensity fields with theoretical predictions, one must be certain that the experimental conditions are carefully matched to the theoretical assumptions. For example, due to extreme saturation effects, minor variations in shape and type of modulation can drastically alter signal form; long-lived three-level systems at low pressure may exhibit some transient response which will be detected in an experiment intended for comparison with a steady-state theory. In addition, such effects as spatial variation of the laser intensity, beam-transit time, and details of the level structure must be considered.

Using an argon ion laser pump beam at 5145 Å and a dye laser probe at 5828 Å, folded three-level Doppler-free resonances have been carefully studied over a wide range of pump intensities (7 mW/cm^2-70 W/cm^2). The co- or counter-propagating beams pass three times through an 80-cm-long cell containing I_2 at low pressure, after which the probe and pump are separated. The pump beam is amplitude-modulated and the change in the probe beam is synchronously demodulated after subtraction of the probe fluctuations yielding high signal-to-background ratio.

In the ac Stark effect studies using co-running waves, a spatially averaged line shape was obtained by observing the gain of the entire probe beam. The line shape in this case is roughly symmetrical and is in reasonable agreement with the steady-state theoretical predictions after averaging the theoretical line shape with

a Gaussian intensity distribution and summing the contributions of all the rotational M levels.

Critical to the shape of the signal at high-saturation parameters is the percentage of pump-amplitude modulation. This effect was studied with an electro-optic modulator at 2 kHz by varying the bias level and the depth of modulation. At high intensities, the line shape is dramatically altered for deviations of only 1% from full modulation. Line shape distortion due to pump modulation frequency and modulation rise time has also been investigated for various pressures and intensities.

Sensitivity of the high-intensity line shapes to the spatial variation of the pump laser field was studied by using a movable pinhole to sample the probe gain as a function of radial position. In the very uniform intensity region near the beam center, the ac Stark-effect signal was found to be highly asymmetric. The symmetry varies with radial position within the Gaussian beam, but it is independent of azimuthal angle. Further investigation of the possible causes for the asymmetric probe signal is under way. Variation of the signal asymmetry with pump intensity, beam size, and pressure is being studied, and a possible contribution to the signal from additional molecular levels is being considered.

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3. OBSERVATION OF ROTATIONAL DEPENDENCE IN COLLISIONAL SELF-BROADENING OF STIMULATED VIBRATIONAL RAMAN SPECTRA IN O_2

National Science Foundation (Grant PHY79-09739)

Bruce W. Peuse, John E. Thomas, Shaoul Ezekiel

We have utilized high-resolution stimulated Raman gain spectroscopy in O_2 to observe the rotational (N) dependence of the collisional self-broadening for

transitions in the fundamental vibrational band.[1] In addition, polarization dependence of the line shapes was investigated. Pump-beam (argon-ion laser) modulation and synchronous detection of the probe beam (dye laser) gain at 8 MHz has enabled shot-noise-limited signal-to-background ratios to be obtained. At atmospheric pressure, the laser linewidth is negligible compared to the resonance full width at half maximum. For Q branch ($\Delta N=0$) resonances obtained with collinearly propagating $\pi^+\pi^+$ polarized laser fields, the resonance full width is found to decrease from a maximum of $\sim$3.1 GHz at N = 9 to $\sim$2.1 GHz at N = 23.

Nonresonant stimulated Raman gain spectroscopy is particularly suited for studying collisional broadening of laser-induced nonlinear resonances, since the linewidth depends only on the initial-to-final state coherence decay rate. In this case, the effective transition operator can be represented as a sum of tensorial components, each of which contributes independently to the line shape. By selecting the relative polarizations of the pump and probe lasers, particular tensorial components of the signal can be enhanced or suppressed. Generally, these components are affected differently by the intermolecular forces and exhibit different decay rates.[2] A study of the effect of dephasing collisions on the linewidth of the individual tensorial components of the signal is of particular interest. Using widely tunable lasers as sources, dependence of the decay rates on rotational and vibrational quantum numbers can be established.

Vibrational nonresonant stimulated Raman spectra in oxygen were obtained using an argon-ion pump (5145 Å) and a tunable ring dye laser (5592 Å). The beams copropagate through a $\sim$200-m path in oxygen at atmospheric pressure by multipass reflection between a pair of high-quality mirrors (88 passes). Various relative polarizations ($\pi^+\pi^+$, $\pi^+\pi^-$, $\sigma^+\sigma^+$, $\sigma^+\sigma^-$) were chosen for the argon-ion and dye laser, respectively.

It is well known[3] that the probe gain signal consists generally of an isotropic part (rank 0 tensorial component) and an anisotropic part (rank 2 tensorial component). For π^+,π^+ (or σ^+,σ^+) relative polarizations of the argon-ion and dye laser fields, both components contribute to the Q-branch spectra. Choosing π^+,π^- (or σ^+,σ^-) relative polarization, however, allows only the anisotropic component to contribute.

The relative area under each Q-branch probe gain vs probe-frequency resonance was determined as a function of rotational quantum number (N). Results for the relative

areas are in good agreement with the theoretical predictions which are expected to be independent of collision parameters.[4] The widths of the resonances varied significantly (about 50%) in going from N = 7 to N = 23. From signals obtained utilizing $\pi^+\pi^-$ or $\sigma^+\sigma^-$ relative polarizations for the lasers, the anisotropic contribution to the Q-branch intensities is found to be much smaller than the isotropic component. Hence, the variation in the widths of the resonances can be interpreted as the variation in the self-broadening of the isotropic component of the resonances with rotational quantum number N.

Since the laser linewidth is negligible compared to the Raman Doppler width, an interesting application of the stimulated Raman gain technique is to study vibrational Raman spectra at low enough pressure so that the Raman Doppler width limit is attained. In this limit, the vibrational dependence of the spin-spin coupling constant may be observable.

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4. MEASUREMENT OF INERTIAL ROTATION USING A PASSIVE RING RESONATOR

U.S. Air Force Geophysics Laboratory (AFSC) (Contract F19628-79-C-0082)

Glen A. Sanders, Robert P. Schloss, Shaoul Ezekiel

The objective of this research program is an investigation into the use of a large passive ring resonator for the measurement of inertial rotation.[1] The sensitivity range we are considering is 10^{-6}-10^{-11} of earth rate which is of considerable interest in geophysics, relativity, and in the testing of precision inertial-grade gyroscopes.

Our present setup is a square cavity, 70 cm on a side, mounted on a super invar

table. The difference between the resonance frequencies of the cavity for clockwise (cw) and counterclockwise (ccw) propagation induced by inertial rotation is measured by a 1/2-mW He-Ne laser, mounted external to the cavity. So far, we have reduced the fluctuation in our measurements to $5 \times 10^{-3}\ \Omega_E$ (τ=1 second) where Ω_E is earth rotation. In contrast, the photon noise limit in our setup is $5 \times 10^{-4}\ \Omega_E$ (τ=1 second).

Once we achieve the photon noise limit in the 70 cm x 70 cm cavity, we plan to set up a 30 m x 30 m cavity in an isolated area below ground. With a 3-watt argon ion laser and this larger cavity the photon noise limit should be a few parts in $10^{-11}\ \Omega_E$ for an averaging time of 1 hour.

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5. MEASUREMENT OF INERTIAL ROTATION USING A MULTITURN FIBEROPTIC SAGNAC INTERFEROMETER

Joint Services Electronics Program (Contract DAAG29-78-C-0020)

James L. Davis, Shaoul Ezekiel

The objective of this program is an investigation into the use of a multiturn fiberoptic Sagnac interferometer for the measurement of inertial rotation.[1] When such an interferometer is subjected to inertial rotation perpendicular to the plane of the fiber ring, a nonreciprocal phase shift is induced for counterpropagating light beams which is proportional to inertial rotation.

We have set up such an interferometer using a 200-m single-mode fiber in order to study a number of techniques for the measurement of small nonreciprocal phase shift in the fiber. So far we have achieved a sensitivity close to that of earth rate, and we anticipate a substantial improvement in the near future.

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6. OBSERVATION OF NATURAL WIDTH DIFFERENCES IN I_2 HYPERFINE STRUCTURE USING HIGH-RESOLUTION TWO-STEP SPECTROSCOPY

National Science Foundation (Grant PHY79-09739)

Richard P. Hackel, Shaoul Ezekiel

We report the observation of differences in the natural widths of I_2 hyperfine structure due to hyperfine predissociation[1,2] in the $B^3\Pi_{o^+_u}$ state. Because these linewidths are very narrow, in the 50-kHz range, we found it advantageous to use a Doppler-free stimulated-resonance Raman technique[3,4] to perform these measurements.

The natural predissociation of the $B^3\Pi_{o^+_u}$ state of I_2 due to the presence of the dissociative $^1\Pi_{1u}$ state produces different lifetimes for different hyperfine sublevels within a given rovibrational level.[1,2] Therefore the natural width of an individual hyperfine component is comprised of contributions from radiative as well as predissociative processes.

For the v' = 43, J' = 12 level in the $B^3\Pi_{o^+_u}$ state in I_2, calculations indicate[3] that the natural widths of individual hyperfine components can vary in the range of 40-120 kHz depending on the nuclear spin for each component. To directly observe such narrow linewidths in a single step, molecular beam or saturation spectroscopy is difficult because of the extremely high resolution that is required. However, by using a resonant two-step excitation scheme in a folded Doppler-broadened system, it is possible to achieve an almost doubling of the upper-level linewidth. This comes about from Doppler averaging in a folded three-level system that is subjected to very weak but counterpropagating pump and probe fields. For such a case, the probed linewidth Γ_s is given by[4]

$$\Gamma_s = \frac{\Omega_s}{\Omega_p}\Gamma_1 + \left(1 + \frac{\Omega_s}{\Omega_p}\right)\Gamma_2 + \Gamma_3, \qquad (1)$$

where Γ_1, Γ_2, Γ_3 are the relaxation rates of the initial, intermediate, and final levels, respectively, and Ω_s,Ω_p are the frequencies of the probe and the pump. If

the initial and final levels are metastable, as in the case of I_2, the probed linewidth is approximately $\left(1 + \frac{\Omega_s}{\Omega_p}\right) \Gamma_2$. If $\Omega_s \approx \Omega_p$, we can get an almost doubling of the upper-level linewidth.

Our experimental setup[2] consists of an 80-cm-long, low-pressure I_2 vapor cell subjected to an argon laser pump and a counterpropagating dye laser probe. Both pump and probe lasers are single-frequency and short-term-stabilized. The pump is held fixed within the Doppler-broadened B-X(43,0), P(13), and R(15) transitions at 5145 Å. The dye laser is scanned over the B-X(43,11), P(13), and R(15) transitions at 5828 Å. The pump is amplitude-modulated at 2 kHz, and the probe is synchronously demodulated in a lock-in amplifier. The $\left(1 + \frac{\Omega_s}{\Omega_p}\right)$ enhancement factor according to Eq. 1 is 1.88 for this setup.

Using this technique, we were successful in observing variations in the linewidths for various hyperfine-structure transitions. For example, the largest difference in width, 57 kHz, occurs for the lines terminating on $|J"I"F"\rangle = |15,1,15\rangle$ and $|15,5,20\rangle$ (similarly for J" = 13). The measured differences in natural widths were used to obtain a direct estimate for the dominant predissociation constants. In addition, we showed that the differences in natural widths were independent of pressure.

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VIII. QUANTUM ELECTRONICS

B. Nonlinear Phenomena

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1. PICOSECOND OPTO-ELECTRONICS

Joint Services Electronics Program (Contract DAAG29-78-C-0020)

Clifton G. Fonstad, Hermann A. Haus

The capability of lasers to produce picosecond pulses has not been exploited by communications technology, because no compact sources of picosecond pulses are available. Laser diodes are the obvious active component for such applications. This is the motivation for the mode-locking work on semiconductor laser diodes initiated in our laboratory over the past several years. The shortest pulses achieved by active mode locking (modulation of the bias current) with uncoated diodes were 16 psec in duration at repetition rates of 2-4 GHz.[1-5] In order to keep the frequency of modulation low, so as to obtain both a satisfactory depth of modulation and high peak power of the mode-locked pulses, external mirrors are used to form a "long" resonator (5-cm spacing for 3 GHz).

Analytic work has shown that the pulse width is limited by the composite Fabry-Perot resonator effect; the uncoated diode in the external resonator acts as an etalon that causes the gain of axial modes to vary periodically with frequency.[6,7] The mode-locked pulses consist of axial-mode clusters, each cluster coherent within itself. The spectral width of the clusters is proportional to the inverse time duration of the pulses. The clusters are incoherent with each other with the result that the mode-locked pulses (of 16-psec duration) contain subpicosecond substructure. Analysis shows that the suppression of the etalon effect requires an antireflection

coating of the diode end face internal to the resonator of very high quality. E.P. Ippen experimented at Bell Laboratories with A.R.-coated diodes in an external resonator[8] (before joining M.I.T. in January 1980) and achieved Fourier Transform-limited pulses of 5-ps duration. He also observed that the mode locking is most effective when it is passive; no μ-wave drive is applied for the shortest pulses achieved. The diodes were self-pulsing when placed in the external resonator due to the unavoidable saturable loss intrinsic to the diodes.[8,9]

We are currently engaged in an effort to integrate the laser diode and external resonator into a compact structure. Our first experiments are centered around a "long" laser structure of 8-mm overall length with divided electrodes that can be separately excited. J. Carney has successfully operated a shorter version of such a structure at room temperature.[10] The electrodes will be excited so as to produce a standing-wave bias-current pattern, with a phase velocity equal to the group velocity of the optical radiation. This form of "integration" obviates the need for a passive waveguide coupled to an active lasing region, a system that would most closely duplicate the diode-external resonator geometry but is more difficult to construct.

In an effort to learn whether mode locking at higher frequencies may produce satisfactory pulses, we are investigating a system designed for 10-GHz mode-locking drive. If mode-locked lasers are to be used for transmission and processing of signals on a picosecond time scale, we must have means for multiplexing and demultiplexing pulse trains containing such pulses. Work is proceeding on the construction of an integrated optical multiplexer in InGaAsP. As a first step toward developing the technology, semi-insulating epilayers are being grown and a coupled waveguide switch is being constructed by Marjorie Johnson. The transverse optical confinement is accomplished by a metallic overlay. The same construction will be used in the multiplexer.

Pulses may be used to sample waveforms; indeed, this is one of several applications envisaged for the mode-locked pulse trains. High-speed sampling may be achieved by other means provided the system is broadband. Optical systems have broad absolute bandwidths and thus may be employed in various ways for this purpose. We are currently developing an integrated optical sampler that consists of four waveguide interferometers[11] in cascade. With cw μ-wave drives of 10, 20, 40, and

80 GHz, respectively, sampling functions with a half-power width of 2 psec can be achieved theoretically. The sampler is envisaged as the central component of a picosecond sampling oscilloscope.

With the aim of developing picosecond pulse-processing systems we are investigating various nonlinear optical processes in order to determine their relative merits for this purpose.

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VIII. QUANTUM ELECTRONICS

C. Distributed Feedback Structures

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1. SURFACE ACOUSTIC WAVE GRATINGS

National Science Foundation (Grant ENG79-09980)

Hermann A. Haus

The impetus for our research in gratings derives from their potential use in integrated optics. Present-day technology is not yet at a state where gratings with periods of the order of 2000 Å can be easily manufactured so that ideas developed for grating resonator-filter design have to be tested in their SAW realization.

The potential of SAW filter design using grating structures is outstanding in its own right. The realization of new SAW structures with interesting characteristics and the analysis of existing structures pose challenging problems.

We have investigated theoretically a filter structure that utilizes coupling of surface acoustic waves to bulk waves to achieve narrow-passband transfer characteristics.[1,2] The structure was proposed originally by Melngailis and Williamson.[3] It has the advantage of utilizing efficient coupling of surface waves to bulk waves that have lower loss and are insensitive to surface aging.

Another investigation focuses on higher order effects (in h/λ_r, where h is the groove depth and λ_r the Rayleigh wavelength) in SAW gratings. The Bragg frequency is a function of $(h/\lambda_r)^2$. Also, the groove reflection is a function of all powers of (h/λ_r) and, in fact, the second-order term can be as large as the first-order term for $(h/\lambda_r) \simeq 0.02$ for trapezoidal grooves of 60° inclination. We have developed a variational principle in support of the analysis with the result that closed-form

expressions have been obtained for all parameters of interest.[4] Because the analysis is simple, it is less error-prone. The only previous publication on the subject was found to be in error.[5]

We hope that a detailed understanding of the effect of groove shape upon the reflection and frequency shift will provide a means for "trimming" of fabricated filters. The lack of the ability to trim SAW grating filters after manufacture has prevented thus far their acceptance in place of bulk wave resonators.

Another project recently initiated is the analysis of diffraction effects in metal-strip grating couplers[6] and RAC devices. The former problem is a natural extension of the work on groove gratings. The latter problem is of great practical importance but has not been analyzed to a degree that is helpful to the RAC designer in suppression of spurious responses produced by diffraction effects.

Experimental work is planned to provide tests for the theories in cooperation with Dr. J. Melngailis of the Materials Science and Engineering Center.

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IX. TIME-RESOLVED SPECTROSCOPY OF CONDENSED MATTER

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1. MICROVISCOSITY IN GELS AND POLYMER SOLUTIONS

Joint Services Electronics Program (Contract DAAG29-78-C-0020)
National Science Foundation (Grants DMR78-23555 and DMR76-80895)

David E. Cooper, J. David Litster

A gel consists of a cross-linked network of long polymer molecules with small molecules of a fluid medium trapped between the polymers. Water is the most common fluid medium and gels containing as much as 99.5% water still exhibit macroscopic shear rigidity. If the cross links are weak (e.g., single hydrogen bonds) they can be broken thermally and a reversible melting transition occurs between the gel and sol phases.

The viscosity of a liquid and its temperature dependence are extremely sensitive to microscopic structural changes. Orientational relaxation times of anisotropic molecules dissolved in a liquid have also been shown to scale with the shear viscosity of the liquid. We have used the reorientation of molecules of the laser dye oxazine-4 perchlorate to probe the viscosity of interstitial water in both gel and sol phases containing gelatine and agarose. Pulses (1 psec, 5 kW) from a mode-locked cavity-dumped dye laser were used to preferentially bleach dye molecules whose transition moments were oriented parallel to the light polarization. Reorientation times were measured by decay of the resulting dichroism.

We found the reorientation times in bulk water to scale with the bulk viscosity. Inside the polymer network of both gelatine and agarose sol and gel phases we found the same temperature dependence of reorientation times as in bulk water and therefore the same activation energy. This indicates the same local structure of water as in

bulk and shows various hypotheses that the gel-sol phase transition is associated with changes in the water structure are incorrect. We also found in gelatine gels an increase in reorientation time of the dye probe as the polymer concentration was increased. This resulted from interference of the polymers with hydrodynamic back flow in the water; by calibration with known behavior in channels of Vycor glass we could estimate the effective pore size in the gel-polymer solution. This varies from 35 Å to 20 Å in 2% to 10% gelatine gels and is in good agreement with estimates by other methods.

2. MOLECULAR REORIENTATION NEAR THE CONSOLUTE CRITICAL POINT

Joint Services Electronics Program (Contract DAAG29-78-C-0020)
National Science Foundation (Grants DMR78-23555 and DMR76-80895)

David E. Cooper, J. David Litster

Nitrobenzene and n-hexane are mutually soluble in any concentration at temperatures greater than about 21°C. Below this critical temperature the contribution of the mixing entropy to the free energy is so small that the mixture separates into two phases, one rich in nitrobenzene, the other in hexane. This type of critical behavior is accompanied by divergences in such quantities as the osmotic compressibility and the coherence length for concentration fluctuations. The static properties of the system have been well characterized experimentally and a satisfactory theoretical explanation is provided by applying the renormalization group method of statistical mechanics to the lattice gas (Ising) model. A mode-mode coupling theory of Kawasaki[1] also provides a good description of the critical behavior of transport properties such as the thermal diffusivity.

The effect of the critical-order parameter fluctuations on molecular reorientation is less well understood. We have used the electric field of the laser pulse to induce a small amount of orientation order (Kerr effect) of the nitrobenzene molecules and studied its relaxation by using a delayed probe pulse to measure the birefringence as a function of time. The order we induced and measured has quadrupolar symmetry and the orientational-order parameter can be represented as a second-rank tensor

$$Q_{\alpha\beta} = \frac{1}{2} \langle 3\zeta_\alpha \zeta_\beta - \delta_{\alpha\beta} \rangle,$$

where $\zeta_\alpha, \zeta_\beta$ are the Cartesian components of the symmetry axis $\vec{\zeta}$ of the molecules and the average is performed over a small but macroscopic volume. The anisotropy in the optical-frequency dielectric-constant tensor (the birefringence) is proportional to $Q_{\alpha\beta}$. A phenomenological model for the dynamical behavior of $Q_{\alpha\beta}$ can be obtained by the same procedure used to describe short-range-order effects in the isotropic phase of a liquid crystal.[2] This predicts an exponential relaxation

$$Q_{\alpha\beta}(t) = Q_{\alpha\beta}(0)\, e^{-t/\tau},$$

where the relaxation time τ is given by

$$\tau = \nu\chi.$$

Here χ is a generalized susceptibility, expected to be only weakly temperature-dependent, and the transport coefficient ν may be expected to be proportional to the shear viscosity of the fluid.[2] We find the reorientation time of nitrobenzene molecules varies from 6.. psec to 11.1 psec as the reduced temperature $t = T/T_c - 1$ varies from 10^{-2} to 10^{-4}. A quantitative analysis of our data is consistent with a weak ($t^{-0.045}$) divergence in agreement with renormalization group calculations[1] for the temperature dependence of the shear viscosity.

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(IX. TIME-RESOLVED SPECTROSCOPY OF CONDENSED MATTER)

3. FUTURE DIRECTIONS

Lenn C. Kupferberg, Brent D. Larson, J. David Litster

We have conducted preliminary experiments on molecular reorientation in the isotropic and nematic phases of the liquid crystal hexylcyanobiphenyl using dye probes in 10^{-4} M concentration. These will be continued and extended to study the effect of orientational order on optical-energy transfer in liquid-crystal phases. We shall also initiate a program to study optical energy transfer in disordered solids; for some of these proposed experiments we shall have to modify our equipment to obtain pulses tunable over a wider range than we can now achieve.

X. INFRARED NONLINEAR OPTICS

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1. INFRARED NONLINEAR PROCESSES IN SEMICONDUCTORS

U.S. Air Force — Office of Scientific Research (Contract F49620-80-C-0008)

Roshan L. Aggarwal, Peter A. Wolff, Y.C. Sunny Yuen, Kathleen Kash, Craig Lindberg, J. Barry McManus, Roosevelt People

Studies of resonant, impurity-induced, four-photon mixing in n-Ge are continuing. During the past year, this technique has been used to study the magnetic field dependence of the valley-orbit splitting in Ge:P and Ge:As. The experiment is similar to an ESR measurement — employing fixed-frequency sources and a magnetic field to tune the energy levels. As anticipated, the valley-orbit splitting varies with magnetic field (B) according to the relation:

$$\Delta(B) = \Delta(0) + \alpha B^2.$$

Our measurements of α lead to the following conclusions:

1. Observed values of α disagree with those predicted by the Lee, Larsen, Lax theory, but agree with a recent calculation by Dr. Larsen. His results show that α is more sensitive to the form of the donor wave function than we had originally expected.
2. α increases with increasing donor concentration (in the 10^{15}-10^{16}/cc range), indicating the onset of electron delocalization for $n \simeq 10^{16}$/cc.
3. Splittings due to off-diagonal matrix elements of the Zeeman interaction are observed in Ge:As.

Semiconductor lasers oscillate at a frequency $h\omega = E_G$; to date, however, laser action has not been achieved for wavelengths greater than about 30 μ, despite the

fact that in a variety of semiconductor alloys the gap can be continuously varied to zero. It is believed that laser action is precluded (for $\lambda > 30\ \mu$) by an exceedingly rapid recombination process, in which electron-hole pairs recombine via plasmon emission. This process can be controlled by a magnetic field, which modifies both the electron-state density and the plasmon dispersion relation. Detailed calculations suggest that, in large fields, the recombination rate can be reduced enough to permit lasing. Two modes of laser action seem possible — one in which plasma modes are excited, then radiate via a finite geometry; and another in which a mixed EM-plasma mode directly emits. Experiments to test these ideas are planned.

A theory of Cardona predicts that $\chi^{(3)}$ of small gap semiconductors varies as $E_G^{-9/2}$. Experiments to test this variation and to explore the resonance enhancement of $\chi^{(3)}$ as $\hbar\omega \to E_G$, are in progress. This work will also study the behavior of $\chi^{(3)}$ when the difference frequency, $\omega_1 - \omega_2$, is matched to a collective mode of the medium. Previous theoretical work indicated strong mixing when $\omega_1 - \omega_2 = \omega_p$; similar effects are anticipated when the difference frequency is matched to a phonon frequency. Both of these processes can serve, in finite geometries, as sources of far infrared radiation.

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XI. QUANTUM OPTICS AND ELECTRONICS

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1. PICOSECOND DYE LASER OPTICS

Joint Services Electronics Program (Contract DAAG29-78-C-0020)
National Science Foundation (Grant ENG79-11380)

Michael M. Salour, Stanley R. Rotman, Richard Bebelaar

We have developed a new method of pulsewidth stabilization of a synchronously pumped dye laser. Our work represents the first attempt to stabilize the pulses by measuring the pulsewidth and maintaining it at a minimum using analog and digital feedback acting, respectively, on the mode-locking frequency and the cavity length of a synchronously pumped mode-locked dye laser. In this way, we have been able to counterbalance the undesirable effects, such as the plasma instabilities in the Ar^+ laser, thermal drift in the cavity length of the dye laser, and the electronic noise in the oscillator that provides the signal for the acousto-optic mode locking of the crystal, which when combined produce fluctuations both in the amplitude and pulsewidth of the picosecond pulses. In this way, we have been able to reproducibly generate pulses as short as 0.7 picosecond.

We have also achieved larger interpulse separation and more energy per pulse by both cavity-dumping and amplifying selected pulses from the cavity dumper in

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synchronism with the frequency-doubled output of an amplified Q-switched Nd:YAG laser. Four stages of amplification are used. We are currently obtaining powers of the order of 3 gigawatts at the repetition rate of 10 Hz with pulses as short as 0.8 picosecond. In addition, we have been able to reproducibly generate sub-picosecond continuums by focusing the output of the last amplifier stage in water.

Publications

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2. NONLINEAR SPECTROSCOPY OF ATOMS AND MOLECULES

U.S. Navy — Office of Naval Research (Contract N00014-79-C-0694)
National Science Foundation (Grant ENG79-08031)

Michael M. Salour, Guillaume M.A. Petite, Bartley C. Johnson, Wulfhard K.H. Lange

We have made the first observation of unidirectional gain in a sodium vapor induced by velocity-dependent light shifts. Our observation was based on creating unidirectional amplified spontaneous emission (ASE) light through Doppler compensation. We have demonstrated that the ASE light intensity depends strongly on the total gain of the medium, $\exp(g \cdot \ell)$, where g is the gain per unit length and ℓ the length. In addition, due to the exponential dependence, we have demonstrated that even a small change of the gain curve width and height will give rise to a dramatic forward/backward (in relation to the compensating laser direction) gain asymmetry, resulting in unidirectional ASE. Our work has also introduced a novel kind of light-induced light switching where the switching is brought about by the rapid relaxation of the population inversion under high forward-gain conditions, and accompanied by a burst of ASE light.

XII. MICROWAVE AND MILLIMETER WAVE TECHNIQUES

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1. RESEARCH OBJECTIVES

National Science Foundation (Grant AST77-26896)
National Aeronautics and Space Administration (Contract NAS5-25543)

Bernard F. Burke

The work of the group emphasizes the development of highly sensitive, stable, wideband receivers, and the use of radio-interferometric methods to achieve high angular resolution at radio wavelengths. The methods use both hard-wired aperture-synthesis interferometers and Very Long Baseline Interferometry (VLBI). Our present emphasis is as follows:

1. Developing low-noise cooled mixers for the wavelength region 3-8 mm. The agreement between calculated and observed noise temperature for a prototype 7-mm mixer is good, and a new broadband model is being developed. The mixers will be used for spectral-line studies of interstellar molecules and for VLBI work.

2. Developing a highly stable multichannel low-noise FET amplifier for 2-cm wavelengths. The system will be cooled, aiming for 1-GHz bandwidth and 100°K system noise. The ultimate goal is to build a radio imagery system for paraboloidal antennas to search for fluctuations in the cosmic microwave background.

3. Making detailed engineering studies for a space VLBI station for use on the NASA space shuttle.

XIII. ELECTRONIC AND OPTICAL MATERIALS AND APPLICATIONS

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Frederic R. Morgenthaler

Our objective is to develop an understanding of magnetostatic and magnetoelastic wave phenomena and to employ them to create novel device concepts useful for microwave signal-processing applications.

Several years ago, work at M.I.T. by Zeskind and Morgenthaler and Cooley proved the feasibility of efficiently coupling, with microstrip lines, to very high-Q tunable microwave resonances in rectangular slabs and disks of single-crystal yttrium iron garnet (YIG).

Our interpretation of these resonances (potentially useful for microwave filtering) is that localized magnetic-mode patterns are formed in which the resonant energies are guided or confined by regions of dc magnetic-field gradient within the crystal. In the first experiments such gradients arose naturally from the nonuniform-shape demagnetizing fields; in subsequent work, we have created prespecified gradients with shaped pole pieces designed by field-synthesis techniques.

This work has two motivations. First, we want to learn whether or not it is feasible to create a multiplicity of tunable, high-Q resonances within the same crystal, whether all at the same frequency or separated by preset amounts. Such a structure could serve as an integrated magnetostatic filter circuit. Second, renewed interest in magnetostatic waves for signal-processing applications in the frequency ranges above L-band (where surface acoustic wave (SAW) has prompted us to inquire whether frequency dispersion, group velocity, and mode-energy distribution can be controlled in a practical manner).

(XIII. ELECTRONIC AND OPTICAL MATERIALS AND APPLICATIONS)

1. MAGNETOSTATIC MODES BOUND BY DC H-FIELD GRADIENTS

Joint Services Electronics Program (Contract DAAG29-78-C-0020)
United States Air Force (Contract F19628-79-C-0047)

Frederic R. Morgenthaler, Robert L. Kyhl, Dale A. Zeskind,
Daniel D. Stancil, Johnny Low

Morgenthaler described two-dimensional magnetostatic modes of a thin ferrite disk that is magnetized normal to its plane by a dc field having radial variation. Specifically, he studied cases where the gradients arise from an r^{2n} field dependence. The model predicts that the rf energy distribution of certain modes can be drastically altered, with attendant changes in the frequency and velocity of energy circulation. These theoretical findings lend strong support to our earlier contention that it is possible to excite modes that are localized or guided by "virtual-surfaces" of discontinuity.

One class of bound mode that emerged from our theoretical studies is that having a "virtual-surface" inside of the crystal that can serve to concentrate and guide the rf energy. Near such a surface the volume divergence of the rf magnetization is very large. Its position is altered by increasing the dc field gradient; some surfaces expand, others contract. It is naturally of interest to determine how great a contraction can take place since cylindrical "virtual-surfaces" with small radii might lend themselves to fairly dense integrated-filter designs. In an effort to study the limiting size of such modes, it is necessary to include the effects of quantum-mechanical exchange. Morgenthaler has done so for a "virtual-surface" unrolled into a plane. D. Stancil has considered the related problems of magnetostatic resonances in one and two dimensions confined by linear and parabolic dc magnetic-field profiles with the effects of exchange included. A number of exact solutions to the model were obtained as well as approximate solutions for the weak gradient limits.

Details of the calculation are contained in a paper to be given at the 1980 Intermag Conference to be held in Boston during the month of April.

2. OPTICAL DETECTION OF MAGNETOSTATIC RESONANCES

Joint Services Electronics Program (Contract DAAG29-78-C-0020)

Nickolas P. Vlannes, Frederic R. Morgenthaler

The doctoral thesis of N. Vlannes will attempt optical detection of localized magnetostatic resonances in thin LPE films of YIG. At infrared frequencies, the magneto-optical response of YIG can be modeled by a dielectric tensor that is dependent upon magnetization. Thus one can probe for the characteristics of the magnetization.

The experiments will make use of our existing Spectra Physics 125 Laser tuned to 1150 nm and new optical detectors capable of responding to approximately 2-GHz modulation rates. A new NRC optical table has been installed, the lens system and detectors procured, and microwave portions of the experiment are being designed.

3. MAGNETOSTATIC WAVES AND DEVICES

United States Air Force (Contract F19628-79-C-0047)
Joint Services Electronics Program (Contract DAAG29-78-C-0020)

Leslie M. Itano, Frederic R. Morgenthaler

A brief statement of the S.M. thesis of Ms. Itano's project follows:

A microwave yttrium-iron-garnet (YIG) delay line can be made to provide linearly dispersive delay with instantaneous bandwidth in excess of 1 GHz in C-band. The dispersion of the device is based on the properties of spin and elastic waves in magnetically biased YIG, a ferrimagnetic material. In particular, linear dispersion can be achieved by first specifying a particular dc magnetic-field profile along the axis of a YIG rod, and then designing the necessary pole pieces with the aid of a computer. The isolation and coupling of the delay line is controlled by the input/output antennae design. Thin flexible wire loops have been used but have proven to be problematic. New thin-film antennae are proposed which should provide more reproducible and reliable coupling. In addition, a new delay-line fixture is proposed which should allow for interchanging of both pole pieces and antennae, opening the

way for a future series of experiments to maximize power-handling capabilities, minimize attenuation, and maximize antenna isolation and coupling.

4. MODE SYNTHESIS

United States Air Force (Contract F19628-79-C-0047)

Johnny Low, Frederic R. Morgenthaler

In our earlier work, we sought and found magnetostatic modes associated with initially given boundary conditions and field gradients. We are beginning to synthesize modes with prespecified characteristics such as velocity of energy circulation and rf energy distribution. In addition, boundary conditions that had been imposed to make the mathematical analysis more tractable (namely, placing the thin film or disk between perfectly conducting planes) can be removed.

When the ground planes bounding the parallel surfaces of a thin-film disk are removed, the outer fringing field can interact along both faces of the disk as well as along the rim. This coupling of inner and outer fields severely complicates the general analysis of resonance modes biased with nonuniform dc fields but is the configuration of greatest practical interest because one normally wishes to avoid generating eddy currents in conductors placed too close to the resonant ferrite.

Fortunately, for very thin disks and weak-to-moderate field gradients, certain simplifying assumptions can be made that allow a relatively simple mode analysis to be carried out for radial gradients of arbitrary form.

The circular disk is modelled as a highly oblate spheroid, and so the resonances studied are quasi-two-dimensional in character.

The results reveal the manner in which mode properties are affected by both the bias gradients and electromagnetic corrections and allow the synthesis of modes with prespecified characteristics, such as frequency, rf energy distribution, and velocity of energy circulation. Because control of that velocity not only affects group delay of signals propagating through the mode but also the rf energy density, we predict that the onset of nonlinear effects due to parametrically induced spin waves should be governed by instability thresholds that are gradient-controllable.

The results of analysis will be presented at the 1980 Intermag Conference in Boston.

5. NEW TECHNIQUES TO GUIDE AND CONTROL MAGNETOSTATIC WAVES

United States Air Force (Contract F19628-79-C-0047)

Daniel D. Stancil, Frederic R. Morgenthaler, Dale A. Zeskind

Our prior research has been concerned largely with transverse variations of a bias dc field that is applied in a direction normal to the plane of the YIG film. It should be noted, however, that novel control of resonance modes and magnetostatic waves can be exercised by employing gradients that arise from a change in the direction of the bias field. If such changes are fairly abrupt, a new type of localized magnetic excitation can result. Such changes will also be accompanied by gradients of the in-plane bias field.

The abstract of a paper to be presented at the 1980 Intermag Conference follows:

The experimental observation of magnetostatic surface waves in a rectangular YIG film placed between strips of permalloy and in the plane of the strips is reported. In such a configuration, the dc magnetic field between the permalloy strips is primarily in-plane with a minimum halfway between and increasing toward each strip. In the presence of such a gradient, a series of discrete modes appears near the low-frequency end of the normally continuous MSSW band. The frequencies of these modes lie below the bottom of the conventional MSSW band as calculated from the field at the center of the sample where the field is minimum. However, reversing the bias field reduces the coupling to these modes, indicating a nonreciprocal surface localization.

Estimates of the group velocities of these modes based on the slope of phase vs frequency data indicate that the discrete modes travel several times faster than conventional MSSWs.

These and other experiments were conducted on uniformly magnetized thin films of yttrium iron garnet (YIG) grown on substrates of gadolinium gallium garnet (G^3) by LPE techniques. Several films approximately 5 microns in thickness have been very kindly supplied to us by Dr. Howard Glass of Rockwell International. They were grown under their U.S. Air Force Contract F44620-75-C-0045.

(XIII. ELECTRONIC AND OPTICAL MATERIALS AND APPLICATIONS)

Publications and Theses

Morgenthaler, F.R., "Two-Dimensional Magnetostatic Resonances in a Thin Film Disk Containing a Magnetic Bubble," presented at the 1978 Conference on Magnetism and Magnetic Materials, Cleveland, Ohio, November 14-17, 1978, p. 2209.

Morgenthaler, F.R., "Synthesized Magnetostatic Resonances in a Nonuniformly Biased Thin Disk without Conducting Boundaries," IEEE Trans. on Magnetics Proceedings of 1980 Intermag Conference held on April 21-24, 1980, Boston, Mass. (to be published).

Stancil, D.D., "Magnetostatic Waves in Nonuniform Bias Fields Including Exchange Effects," IEEE Trans. on Magnetics Proceedings of 1980 Intermag Conference held on April 21-24, 1980, Boston, Mass. (to be published).

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XIV. MICROWAVE THERMOGRAPHY

Academic and Research Staff

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J.J. Daly, B.R. Rosen

National Institutes of Health (Grant 5 R01 GM20370)

Alan H. Barrett, Philip C. Myers

During the past year we have taken data at a frequency of 6 GHz on approximately 1000 patients at the Sagoff Breast Cancer Detection Clinic at Faulkner Hospital in Boston. The 6-GHz system has included a microprocessor and hard-copy unit so that the microwave data can be reduced as soon as the examination is over, and the copy of the reduced data becomes a part of the patients' records. The number of malignancies, confirmed by biopsy, was 35. Our best detection statistics have been derived by taking a linear combination of three quantities computed from the microwave data. These are: (1) the temperature difference between symmetrically opposite positions on the right and left breasts (nine such differences per patient); (2) the average temperature of the right breast minus the average for the left; and (3) the temperature of the hottest position minus the average temperature of that breast. Items (1) and (2) reveal right-left asymmetries, whereas (3) may indicate a region of anomalously high temperature. The results of computations (2) and (3) and the maximum difference in (1) are displayed on the CRT terminal at the conclusion of the examination and printed out on the paper copy. The results are a true positive detection rate of 0.85 and a true negative rate of 0.72. These are significantly better than our previous results but are not necessarily due to the higher frequency used.

The 3-GHz radiometer has been completely rebuilt and is currently in use at Faulkner Hospital with the 6-GHz radiometer and the microprocessor. The two frequency data will provide a measure of the temperature gradient within the breast as well

as the temperature distributions. It is hoped that the additional information will lead to improved detection statistics.

XV. RADIO ASTRONOMY

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1. LONG-BASELINE ASTROMETRIC INTERFEROMETER

National Science Foundation (Grant AST77-06052)

Michael Shao, David H. Staelin

A one-inch aperture prototype stellar interferometer was shipped to Mt. Wilson Observatory last year. The interferometer first tracked the white-light fringe in March 1979. The servo maintained equal path lengths in the two arms of the interferometer to 0.1 μm with a three-stage optical delay line. The fringe position was measured to 0.03 μm precision with 220 detected photons every 4 milliseconds. The optical bandwidth of the interferometer was 0.4 μm to 0.9 μm. Extrapolating from the fringe tracking data, the current tracking algorithm will track the fringes from 8.7 mag stars using 12-cm aperture optics.[1]

Two-color fringe measurements were made in June of 1979. For a 1-second integration time, two-color measurements were more accurate by approximately a factor of 3 over one-color measurements.

We have started work on phase two of the interferometer program, where we hope to demonstrate the elimination of atmospheric, thermal, and seismic errors at the milli-arc-second level.

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2. CONTROLLED THIN-FILM ANTENNA

Joint Services Electronics Program (Contract DAAG29-78-C-0020)

David H. Staelin, Timothy L. Johnson, Jeffrey H. Lang, James R. Melcher

The use of electrostatic charges for rapidly manipulating a thin membrane is being studied as a method for precisely controlling the shape of reflector antennas of ∿10-300 meter diameters in space; ground-based versions ∿2-10 meter diameter may also be of interest. This year the control experiments on the 1-meter square membrane were completed and rms surface tolerances of ∿10 μm rms were obtained in the presence of an electric pressure twice that necessary to destabilize the system; ∿30-100 μm rms were obtained at four times the basic destabilization pressure and three unstable modes were then controlled.

It was shown this year that the minimum diffraction-limited 3-dB beamwidth θ_B of such an antenna is approximately limited by

$$\theta_B(\text{radians}) \simeq \frac{1}{3AN(f/D)} ,$$

where N is the number of controlled modes, A is a factor near 10 which represents the intrinsic curvature of the reflector surface, and f/D is the reflector's ratio of focal length to diameter. Because the number of independent electrostatic control elements is limited by the antenna geometry and by Laplace's equation, it can be shown that one limit to resolution θ_B is

$$\theta_B(\text{arc sec}) \gtrsim \frac{900}{AM^2(f/D)^3} ,$$

where M is the number of controlled instabilities. For example, an antenna with f/D = 1 might achieve θ_B = 10 arc sec with 690 control elements and 3 controlled instabilities.

These experimental and theoretical results favor the development of this technology for space applications, and perhaps for terrestrial systems designed for submillimeter and millimeter wavelengths.

3. SCANNING MICROWAVE SPECTROMETER EXPERIMENT

National Aeronautics and Space Administration (Contract NAS5-21980)

David H. Staelin, Philip W. Rosenkranz

The five-channel Scanning Microwave Spectrometer (SCAMS) yielded 10 months of data from the Nimbus-6 satellite, launched in 1975.[1]

Analysis of Typhoon June (1975) demonstrated that the radial derivative of microwave brightness temperature is related to the vertically weighted tangential wind through a wind weighting function; this relation follows from the thermal wind equation. Agreement with simultaneous 700-meter aircraft reconnaissance winds was good except near the eye of the typhoon, where the 150-cm resolution of SCAMS limited the performance.[2]

Snow and ice observations by SCAMS as a function of view angle and frequency have provided evidence that the microwave behavior of firn (long-term accumulated snow in Antarctica and Greenland) can be explained largely by the existence of random layering in the bulk of the firn with a vertical correlation length on the order of a millimeter; the variance in dielectric constant for these layers appears to grow as the ice grains grow with time and depth.[3] Similar studies of sea ice suggest that more isotropic bulk scattering dominates its radiometric signature.[3]

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4. TIROS-N SATELLITE MICROWAVE SOUNDER

U.S. Department of Commerce — National Oceanic and Atmospheric Administration
(Grant 04-8-M01-1)

David H. Staelin, Philip W. Rosenkranz, Paul Toldalagi

The first two satellites of the operational Tiros-N series have been launched; each incorporates a four-channel passive microwave spectrometer operating in the 50-58 GHz band.

Linear statistical estimators and Kalman filters were developed to retrieve temperature profiles from this data, the latter providing improvements in rms errors of ∿20 percent, comparable to earlier results with microwave data from the Nimbus-6 satellite. The most interesting result concerning Kalman filters was that incorporation of second-order statistics based on the actual local three-dimensional temperature field did not significantly improve the retrieval performance for summer data; it generally suffices to incorporate only the average latitudinal dependence and simple correlation constants between adjacent parcels of air. Significant improvement was prevented in part by the conflict between adequacy of representation and adequacy of statistics characterizing that representation.

A statistical view of linear retrieval techniques has led to a novel and useful procedure for updating statistical measures used in the retrieval of temperature profiles from Tiros-N data. The method has particular value over ocean, and should be incorporated in operational data interpretation procedures. In essence, the technique uses the variable scan angle of the microwave sounder to improve knowledge of the mean temperature profile, including certain components that may be invisible to the instrument at certain angles.

5. SCANNING MULTICHANNEL MICROWAVE RADIOMETER (SMMR)

National Aeronautics and Space Administration (Contract NAS5-22929)

Philip W. Rosenkranz, Timothy S. Bigelow, William T. Baumann, David H. Staelin

The SMMR is an instrument on the Nimbus-7 satellite.[1] The objective of our research is to use the measurements to infer parameters which characterize the state of the atmosphere-ocean surface system. The parameters which we have found

possible to retrieve using this instrument are sea surface temperature, near-surface wind speed, integrated water-vapor content, integrated liquid-water content, and a characteristic radius of the drop-size distribution function. The inversion method which we have developed is one which operates on each spatial Fourier coefficient of the antenna temperature images (at five frequencies and two polarizations) to estimate the corresponding spatial Fourier coefficients of the geophysical parameters.[2,3] Efforts are also being made to improve models for the calculation of brightness temperatures given a specified state of the atmosphere-ocean system, particularly when the surface emissivity is increased by wind-generated white water and roughness.

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6. COMMUNICATION SATELLITES

National Aeronautics and Space Administration (Contract NAS5-25091)

David H. Staelin

In the late 1980's it will become practical to transfer a large fraction (perhaps 30 percent) of all long-distance telecommunications traffic to satellites, a step which will require significant switching capacity in space.[1-3] Analysis of market and technology issues has resulted in definition of a minimum-cost TDMA satellite-communications system architecture that could serve the entire United States by handling 30 GHz traffic. More than 1000 ground stations operating at 20,30 GHz would couple existing local toll centers or other nodes to a complex of very similar satellites sharing a single synchronous orbital slot. One novel feature of this architecture is the simultaneous use of more than one cooperating switched satellite with little intersatellite communication.

The projected costs for such a system appear to be very attractive and could facilitate establishment of new services such as video conferencing.

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7. MICROWAVE SPECTROSCOPY OF THE INTERSTELLAR MEDIUM

National Science Foundation (Grant AST77-12960)

Alan H. Barrett, Philip C. Myers

In 1979 Professors Barrett and Myers and their students carried out the following radio astronomical investigations of dense molecular clouds: (1) a study of the dense neutral globules in the Rosette Nebula; (2) a study of NH_3 emission from the galactic center; (3) a survey of nearby reflection nebulae in spectral lines of CO and NH_3; (4) first detection of the J = 3 doublet line of H_2CO in Orion; (5) searches for new regions of emission from the rare molecule HC_5N (six such regions were found); (6) large-scale mapping (full coverage of several square degrees) of CO emission from the nearest star-forming complexes in Taurus and Ophiuchus; and (7) construction of radiative transfer models permitting analysis of asymmetrical spectral lines in terms of cloud motions. These observational programs are part of our attempt to understand the formation and evolution of dark clouds in the interstellar medium and how they may relate to star formation. These programs, and others like them, will be continued in the coming year.

8. RESEARCH OBJECTIVES

National Science Foundation (Grant AST77-26896)

Bernard F. Burke

The radio astronomy program covers a broad range of galactic and extragalactic problems. Some of these require equipment built in our laboratory, and some are carried out at large national facilities. The major research thrusts are as follows:

1. Performance of VLBI studies of celestial radio sources at a variety of wavelengths, to understand the physical processes in quasars and active galaxies. Long-wavelength (0.5-1 m) systems are being built and tested; the mm-band mixers under development will be used at the Haystack Observatory and elsewhere. Observations at standard VLBI frequencies will use existing equipment.

2. Study of time variations of interstellar masers, using VLBI methods to obtain maps with milli-arc-second accuracy. Time variations of adjacent maser spots would provide evidence for shock motions in maser complexes.

3. Completion of a large-scale survey of equatorial radio sources, using the 300-ft transit telescope of NRAO at Green Bank. Initial wavelength is 6 cm; observed sources will be reobserved at other wavelengths to determine spectra.

XVI. ELECTROMAGNETIC WAVE THEORY AND REMOTE SENSING

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1. ELECTROMAGNETIC WAVES

Joint Services Electronics Program (Contract DAAG29-78-C-0020)

Jin Au Kong

Electromagnetic waves are studied with applications to microwave remote sensing, geophysical subsurface probing, microstrip antenna problems, and optical beam diffraction by periodic structures. Acoustic waves are also being studied with application to geophysical exploration. Refereed journal articles and conference papers published in the past year are listed in the references. Second-order coupled-mode equations have been used to study the diffraction of optical beams by a periodically modulated layer.[1] The use of acoustic and electromagnetic waves in geophysical exploration has been studied.[2-5] Extensive work has been accomplished on theoretical modeling and data interpretation for active and passive microwave remote sensing.[6-17] Microstrip antenna problems, relating to the study of radiation fields, resonance phenomena, electric capacitance, and input impedance, have been carried out with rigorous analytical approaches.[18-25] Multiple-scattering effects of acoustic and electromagnetic waves by random distribution of discrete scatterers are being studied using coherent potential and quantum-mechanical formalism.[26-27]

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2. REMOTE SENSING WITH ELECTROMAGNETIC WAVES

National Science Foundation (Grant ENG78-23145)

Jin Au Kong

Active remote sensing with dipole antennas and line sources has been studied for both monochromatic and pulse excitations.[1-3] Extensive work has been accomplished on theoretical modeling and data interpretation for active and passive microwave remote sensing with radars and radiometers.[4-19] Multiple scattering effects of electromagnetic waves by a random distribution of discrete scatterers are being investigated for application to remote sensing of earth.[20]

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3. ACTIVE AND PASSIVE MICROWAVE REMOTE SENSING

National Aeronautics and Space Administration (Contract NAS5-24139)

Jin Au Kong

In the active and passive microwave remote sensing of low-loss and scattering-dominant areas, the effects of volume scattering are very important in the backscatter and brightness temperature measurements. The scattering effect can be accounted for by considering the scattering to be due to either discrete scattering centers imbedded in a homogeneous medium (discrete-scatterer approach) or by considering inhomogeneities in a medium (random-medium approach). We have used both the discrete-scatterer approach and the random-medium approach with the radiative transfer theory to study the effect of volume scattering.[1-10] We also used the Born approximation to develop theoretical models for the active remote sensing of layered random media.[11-13] The results have been applied to interpret the data obtained from vegetation and snow-ice fields. The radiative transfer theory was justified from a more rigorous wave theoretical approach, and the modified radiative transfer theory which includes the coherent effect is being derived.[14-16] Energy conservation and asymptotic solution for the reflectivity of a very rough surface have been studied.[17-18]

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4. PREDICTION OF BACKSCATTER AND EMISSIVITY OF SNOW AT MILLIMETER WAVELENGTHS

U.S. Air Force – Eglin (Contract F08635-78-C-0115)

Jin Au Kong

In the microwave remote sensing of snow, volume scattering effects play a dominant role in the backscatter and brightness temperature measurements. Radiative transfer theory has been used to develop theoretical models applicable to the active and passive remote sensing of scattering-dominant layered media.[1-9] The Born approximation has been applied to the active remote sensing of layered random media.[10-12] These theoretical results have been used extensively to interpret the data collected from snow fields. The validity of the radiative transfer theory has been justified by a more rigorous wave theoretical approach.[13] Energy conservation for reflectivity and transmissivity at a very rough surface has been investigated.[14]

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5. ACOUSTIC-WAVE PROPAGATION STUDIES

Schlumberger Doll Research Center

Jin Au Kong, Leung Tsang

Asymptotic solutions for the first compressional head wave arrival in a fluid-filled borehole have been investigated.[1] Transient solutions due to line and point sources in a slab medium have been obtained with the double deformation technique.[2-3] Numerical evaluation of the transient acoustic waveform due to a point source in a fluid-filled borehole has also been studied.[4] The study of microstrip disk resonance and capacitance is being rigorously carried out.[5-10] The problems are treated as mixed boundary value problems and are being investigated through various mathematical approaches. The validity of the radiative transfer theory has been justified by a rigorous wave theoretical approach.[11] Multiple scattering effects of acoustic and electromagnetic waves by random distribution of discrete scatterers are being studied using coherent potential and quantum mechanical formalism.[12-13]

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XVII. ELECTRONIC PROPERTIES OF CHARGED CENTERS IN SiO_2-LIKE GLASSES

Academic Research Staff

Prof. M.A. Kastner

Graduate Students

C.M. Gee

Joint Services Electronics Program (Contract DAAG29-78-C-0020)

Marc A. Kastner

Defects in amorphous (a-) SiO_2 are thought to result in deleterious optical and electronic effects. They may be responsible for limiting the transmission of optical fibers; they may be the origin surface states at Si-SiO_2 interfaces which trap charge carriers; they probably cause potential fluctuations which scatter mobile carriers moving near the Si-SiO_2 interface. Both of the latter effects seriously limit the performance of MOS devices.

A wide variety of techniques has been employed to study the defects in a-SiO_2, and a great deal is known about them. However, the electronic structure and properties of the intrinsic defects are not yet well established. On the other hand, much progress has been made in developing detailed models for intrinsic defects in narrower band gap chalcogenide glasses (e.g., Se, As_2S_3, As_xTe_y, etc.). The models have been successful in explaining Fermi-level pinning in the diamagnetic ground state and a wide variety of excited-state properties. The model of Kastner, Adler, and Fritzsche strongly emphasizes that the nature of the defects is a result of the special chemical bonding in materials containing two-fold-coordinated group VI elements. Therefore, it was proposed that defects similar to those in sulfides, selenides, and tellurides would be present in oxide glasses as well.

The most valuable probe of defects in semiconducting glasses has been photoluminescence (PL). The large PL Stokes shift and linewidth provided evidence for the strong electron-phonon coupling necessary to explain the effective attraction between electrons (Anderson's effective negative correlation energy). We therefore undertook a program solely under JSEP funding to study PL in a-SiO_2.

(XVII. ELECTRONIC PROPERTIES OF CHARGED CENTERS IN SiO_2-LIKE GLASSES)

This program has recently had its first success. We were the first to observe intrinsic photoluminescence in a-SiO_2. The results have just been published [Phys. Rev. Letters 42, 1765 (1979)]. Although some features of the PL are different from those in sulfide and selenide glasses, these differences are quantitative rather than qualitative. We found that the PL spectra of SiO_2 and other glasses scale with band gap. Neutron irradiation increases the PL intensity and increases the optical absorption in the excited band to levels higher than could arise from impurities showing that the luminescence centers are intrinsic defects. The scaling of the PL and PLE spectra with band gap is strong evidence that the intrinsic defects in SiO_2 have structure similar to those in other chalcogenide glasses.

A second remarkable scaling was also discovered. The exponential decrease of PL quantum efficiency with temperature for all chalcogenide glasses indicates that the activation energies Δ for nonradiative processes must have a distribution of the form

$$g(\Delta) = e^{-\Delta/kT_o}/kT_o.$$

The spread of activation energies kT_o is found to be proportional to the glass transition temperature T_g. Thus when temperature is normalized to T_g, the temperature dependence of the quantum efficiencies of different glasses superpose. Experiments are now under way to measure time-resolved PL spectra using a pulsed F_2 laser (10-nsec pulse, 1 MW, 1575 Å) as the excitation source.

XVIII. PHOTON CORRELATION SPECTROSCOPY AND APPLICATIONS

Academic and Research Staff

Prof. S.-H. Chen
B. Herpigny

Graduate Students

P. Wang

1. RESEARCH PROGRAM

National Science Foundation (Grant PCM78-15844)

Sow-Hsin Chen

A high-resolution spectroscopic technique based on scattered light intensity fluctuation measurement has been in use for some time. Our method is a variation of the digital time-domain pulse correlation technique using a 256-channel clipped correlator developed in the laboratory. The correlator-multichannel memory system is controlled by a PDP 11/MINC computer system which is capable of high-speed data acquisition and analysis necessary for the study of time-varying phenomena.

We have developed theoretical methods to calculate quasi-elastic light-scattering spectra from cells undergoing Brownian motions or self-propelled motions in liquid media. The methods have been successfully tested with extensive photon correlation measurements on Escherichia Coli bacteria, and applicability of the model calculation to cells of dimensions of the order of a micron has been ascertained. The photon correlation technique will be further developed to incorporate a flow method which permits us to study time-dependent phenomena with a temporal resolution greater than the time taken for the accumulation of the correlation function. The combined theoretical and experimental progress now enables us to perform the following three categories of experiments:

a. Motility characteristics of bacteria in response to external stimuli;

b. Study of traveling-band formation of bacteria as a result of chemotaxis; and

c. Study of conformational change in globular protein induced by disruption of hydrophobic interactions.

(XVIII. PHOTON CORRELATION SPECTROSCOPY AND APPLICATIONS)

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XIX. MICROSTRUCTURE FABRICATION

Academic and Research Staff

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Dr. H. Von Känel

Graduate Students

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1. CREATION OF THE SUBMICROMETER STRUCTURES LABORATORY

National Science Foundation (Grant ENG78-10436)
M.I.T. Sloan Fund for Basic Research

Henry I. Smith, John Melngailis

The goals of the Submicrometer Structures Laboratory are to develop methods of fabricating surface-relief and doping structures with linewidths ranging from 100 Å to a few micrometers and to use these structures in a variety of research projects.

The administrative structures and funding for the Laboratory were established early in 1978. Laboratory renovations were started in August of 1978 and the main pieces of equipment were installed in December of 1978. The Laboratory was inaugurated on May 8, 1979.

The Submicrometer Structures Laboratory has the following capabilities:

- substrate cleaning and contamination-free handling
- photolithography
- holographic lithography
- x-ray lithography
- ion beam etching
- plasma etching
- reactive ion etching
- advanced optical microscopy
- electron-beam evaporation
- surface profilometry.

The Laboratory is closely coupled to a similar but larger facility at Lincoln Laboratory which is also directed by H.I. Smith. The Lincoln Laboratory facility has all of the above capabilities as well as electron-beam lithography.

In addition to the research programs described under separate headings below, the Submicrometer Structures Laboratory collaborates in a number of other research projects. The grating in the $Pb_{1-x}Sn_xTe$ distributed feedback laser in the thesis work of H.H. Hsieh was ion beam-etched in the laboratory. S. Frankel of Harvard and the Peter Bent Brigham Hospital is designing and will build miniature thin-film electrodes to be used to probe electrical signals in individual living cells. S. Asoury has used the ion beam-etching apparatus in a charge-flow transistor project. These are a few examples where the unique capabilities and equipment of the Submicrometer Structures Laboratory have made possible or facilitated other research projects at M.I.T.

2. DEVELOPMENT OF MICROSTRUCTURE FABRICATION TECHNIQUES

Joint Services Electronics Program (Contract DAAG29-78-C-0020)

Stephane S. Dana, Andrew M. Hawryluk, Robert F. Kwasnick,
John Melngailis, Henry I. Smith

The objective of this program is to establish reliable techniques for fabricating artificial microstructures, such as surface-relief structures and doping profiles, having dimensions ranging from 100 Å to a few micrometers. In some cases the effort consists of acquiring technologies developed at M.I.T. Lincoln Laboratory or elsewhere. In other cases the technologies are refined or extended in specialized manners. The following technologies are being established and developed:

- conformable photomask lithography
- holographic lithography
- x-ray lithography
- spatial-period division
- shadowing
- reactive ion etching
- plasma etching
- ion beam etching.

3. GRAPHOEPITAXY

U.S. Navy – Office of Naval Research (Contract N00014-79-C-0908)
M.I.T. Cabot Fund

Krikor A. Bezdjian, Stephane S. Dana, John Melngailis, Henry I. Smith

Recently, D.C. Flanders and H.I. Smith at M.I.T. Lincoln Laboratory demonstrated that oriented crystalline overlayers could be obtained on amorphous substrates by first producing an artificial surface-relief structure in the substrate. The technique is called graphoepitaxy. In collaboration with M.W. Geis, graphoepitaxy was demonstrated for Si over SiO_2 in 1979. In the Submicrometer Structures Laboratory graphoepitaxy research is pursued along two avenues: basic studies of nucleation and growth over surface-relief structures; and development of graphoepitaxial approaches to solar cells. Our studies of nucleation and growth have focused on silicon and GaAs deposited by chemical vapor deposition (CVD). Recently, ion beam sputtering of Si has been added. Gratings are fabricated in Si_3N_4 membranes about 2000 Å thick. Thin films are grown over these gratings and the phenomena of nucleation and island formation are studied by transmission electron microscopy. As expected, the artificial surface-relief structures have a profound effect on film growth.

The research on graphoepitaxy for solar cells is concentrating on crystallizing amorphous Si films over artificial surface gratings in carbon or other conducting substrates.

4. ATTACHMENT AND PROPERTIES OF MOLECULES ON SUBMICROMETER STRUCTURES

U.S. Navy – Office of Naval Research (Contract N00014-79-C-0908)

Dale C. Flanders, Manfred M. Kappes, Ralph H. Staley

Techniques are being developed to provide area-selective covalent attachment of chemicals to artificial microstructures. Research has centered on linking specific classes of compounds to silica surfaces by means of silane reagents. Techniques have been explored which provide uniform thin-film coverages of the order of a monolayer. Complementary work has been pursued in three related areas: (1) chemically blocking

the attachment-active sites on silica, (2) attachment to an anodized gold surface, and (3) transition metal complexation to surface-attached ligands. Initial applications of these attachment procedures have focused on surface-conductivity measurements across 2 micrometers of chemically modified silica surfaces. By choosing the correct mode of surface derivatization it is possible to prepare sensors in which surface conductivity is modulated as a result of changes in the chemical environment of the attached species.

5. ELECTRONIC TRANSPORT IN QUASI-ONE-DIMENSIONAL SUBMICROMETER STRUCTURES IN SILICON INVERSION LAYERS

Joint Services Electronics Program (Contract DAAG29-78-C-0020)

Marc A. Kastner, Robert F. Kwasnick, John Melngailis

There is a great deal of recent interest in the behavior of electrons confined to one dimension. In particular, reduced dimensionality is expected to reveal the strong effects of localization, electron-electron, and electron-phonon interactions. For example, Thouless has argued that all wires are insulators at sufficiently low temperature. The effects of electron-electron and electron-phonon interaction should be dramatic if electrons can be confined to two-dimensional quantum levels but kept free in the third dimension. Inversion layers on the surface of silicon have been used to quantize the energy levels in one dimension, creating a two-dimensional electron gas. We are extending this technique to create a one-dimensional electron gas. Using the facilities of the Submicrometer Structures Laboratory, we are attempting to fabricate a quasi-one-dimensional inversion layer in Si in a field-effect transistor-type structure.

6. X-RAY LENSES AND DIFFRACTION GRATINGS

Lawrence Livermore Laboratory (Subcontract 206-92-09)

Marsden P. Griswold, John Melngailis, Henry I. Smith

Under this program, techniques for fabricating x-ray zone plates are developed at M.I.T. Lincoln Laboratory, and techniques for making x-ray diffraction gratings

are developed in the Submicrometer Structures Laboratory. Testing is done at Lawrence Livermore Laboratory. Zone plates were fabricated with minimum zone widths of 3000 Å, and imaging with 1-micrometer resolution was demonstrated. The next generation of zone plates will involve 1000 Å zone widths.

7. SUBMICROMETER STRUCTURES AND LIQUID-CRYSTAL RESEARCH

U.S. Navy – Office of Naval Research (Contract N00014-79-C-0908)
National Science Foundation (Grant DMR78-23555)

J. David Litster, John Melngailis, Henry I. Smith, Hans Von Känel

Well-aligned phases of liquid crystals are necessary for studies of their properties by means of scattering spectroscopy. The objective of this program is to use artificial-surface microstructures, such as gratings, to induce uniform alignment of liquid-crystal phases. Various liquid crystals have been aligned on surface-relief gratings of 1-micrometer period etched into fused-silica substrates. Alignment of butoxybenzylidene-p-oktylanilene established in the nematic phase could be retained down to almost one degree below the nematic-to-smectic transition. Farther below this the formation of focal conics could not be prevented but the defects could be removed entirely by heating the sample into the nematic phase. By reducing the spatial period of the gratings, we hope to reduce the number of focal conics in the smectic A phase which should enable us to investigate the smectic A-to-smectic B phase transition.

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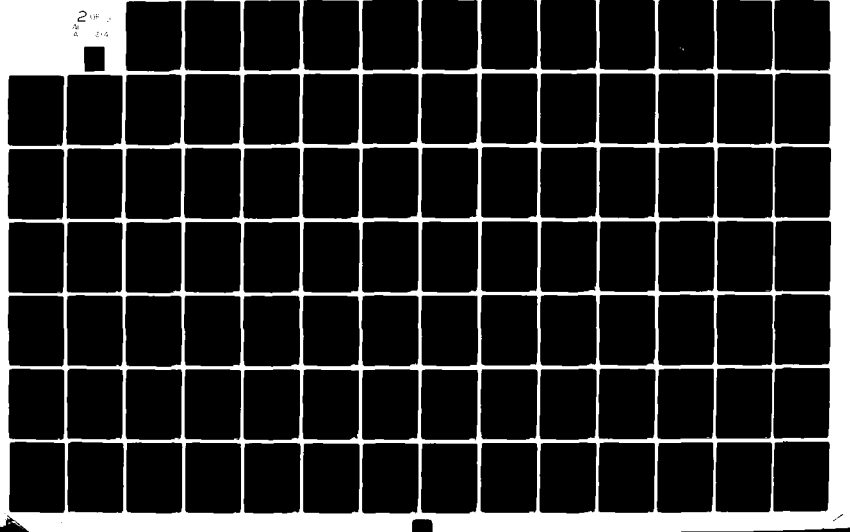

PLASMA DYNAMICS

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XX. PLASMA DYNAMICS

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XX. PLASMA DYNAMICS

A. Basic Plasma Research

1. NONLINEAR WAVE INTERACTIONS

National Science Foundation (Grant ENG79-07047)

Abraham Bers, Robert H. Berman, Kwok C. Ko, Vladimir B. Krapchev, Abhay K. Ram, Kim S. Theilhaber, Maria Elena Villalon

Progress is reported in theoretical and computational work aimed at understanding the behavior of large-amplitude coherent waves in a plasma. Three specific research projects are briefly described.

(a) Nonlinear Waves in a Vlasov Plasma

The one-dimensional Vlasov equation for the electrons has been solved for a general form of the potential and to all orders in the field amplitude.[1] The distribution function is determined uniquely in terms of the action, which is the adiabatic invariant in the problem. In our approach the system evolves to its nonlinear state, in contrast to the stationary BGK solution.[2] The theory predicts the existence of a trapped-particle mode above a certain threshold for the field amplitude. Recent experimental observations confirm this prediction.[3]

(b) Stochasticity in Plasma Dynamics

Many problems involving the change from ordered to chaotic motion in Hamiltonian systems can be reduced to a simple two-dimensional mapping on a unit torus. The local work of Chirikov and Greene[4,5] on the standard mapping is extended to provide global measures of stability. Our local and global studies of difference equations with periodic coefficients show that well-developed stochastic behavior is observable below the Chirikov threshold.[6,7] We have obtained preliminary results on the onset of stochastic particle motion in a finite-amplitude wave packet.

(c) Space-Time Evolution of Wave-Wave Interactions

Resonant parametric instabilities can occur when a large amplitude lower hybrid wave is excited in a tokamak plasma. We study the decay into a low sideband of the

pump and a low-frequency mode. During the past years an effort has been made to understand the effects of wave-numbers mismatch and finite spatial extent of the pump.[8-10] These works have focused mainly on numerical solutions. We have carried out an analytical study and reported the results.[11]

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2. RENORMALIZATION METHODS IN PLASMA TURBULENCE THEORY

National Science Foundation (Grant ENG79-07047)

Thomas H. Dupree

Plasma fluctuations with velocities of the order of or less than the thermal velocity are being studied. In the stationary case, these fluctuations are known as B.G.K. modes. In the turbulent case, they have been referred to as clumps. A clump is an excess or deficiency in the local phase density as compared with the local average density. We can picture the deficiency case as a hole, and it has the interesting property of being gravitationally bound. These structures persist on a long time scale in the plasma and have important effects on a variety of plasma phenomena. The earlier theory of these fluctuations is being improved and a more

rigorous theory developed. In particular, the new theory conserves both the electric energy of the fluctuations and the kinetic energy of the particles.

3. INTENSE RELATIVISTIC ELECTRON BEAMS

National Science Foundation (Grant ENG79-07047)
U.S. Air Force — Office of Scientific Research (Grant AFOSR-77-3143)

George Bekefi

During the past year our major experimental and theoretical effort has been in the generation of coherent microwave and submillimeter radiation using intense relativistic electron beams. Our interest was concentrated on free-electron lasers and magnetrons. Below we describe four pieces of research in which we have been active.

a. A Free-Electron Laser Pump Produced by Magnetic Diffusion

An efficient, quasi-static magnetic wiggler for use in free-electron lasers is produced by diffusing a time-varying magnetic field through a spatially periodic conductor, such as an assembly of copper rings or a copper helix. In our experiments, the magnetic field is generated in a 2275 turn, 1-m-long solenoid driven by a 3750-μF, 4-kV capacitor bank. At full capacitor charging, and in the absence of the periodic conductor, the solenoid current peaks at 720 A in a time of 17 ms, producing a uniform axial magnetic field B_z = 21 kG.

When a set of uniformly spaced copper rings (see Fig. XX-1) is used as the diffusive medium, the resulting magnetic field has the desired spatially periodic radial component B_r, together with a spatially modulated axial field B_z. The left-hand side of Fig. XX-1 shows the magnetic field components measured at a distance r = 0.86 cm from the solenoid axis when the capacitor bank is fully charged to 4 kV and the wiggler periodicity ℓ = 4 cm. The right-hand side of Fig. XX-1 gives the dependence of B_r on the periodicity ℓ, and shows that large pump amplitudes can be achieved by this technique.

In FEL applications, it is desirable to gradually increase B_r as the electron

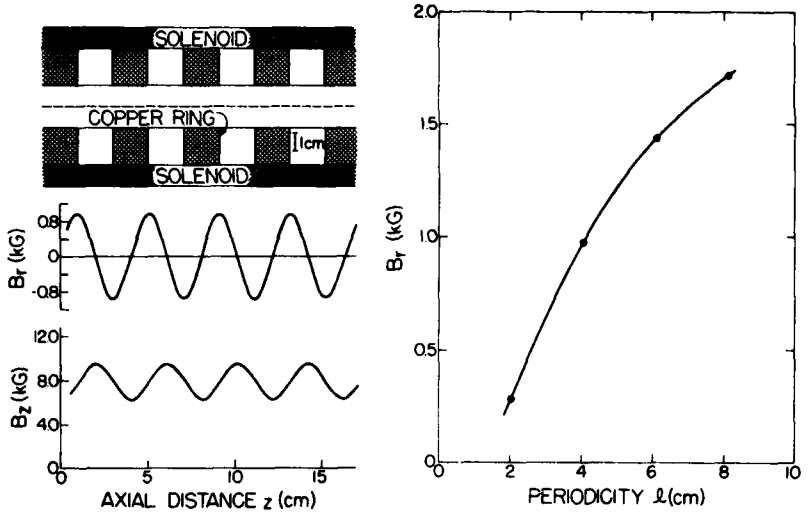

Fig. XX-1.

beam enters the interaction region. This is readily done by increasing the radial thickness of the rings as one moves away from the electron gun. Approximate calculations were carried out which allow one to optimize the thickness of the rings and estimate the values of B_r and B_z.

As an alternative to the rings, a helical copper bar has been used as the diffusive structure. This yields a helical magnetic pump whose properties are also being investigated.

b. A Study of Field Emission Diodes for FEL Applications

Relativistic electron beams exhibiting laminar, monoenergetic electron flow are required for use in free-electron lasers (FEL). Experimental[1] and computer simulation[2] studies indicate that foilless field-emission diodes used in stimulated Raman FEL systems do not possess the desired performance characteristics. One manifestation of poor beam quality (which we in fact use as a diagnostic) is the copious emission of microwave radiation. Power levels of 100-1000 kW have been observed when the beam emanating from the gun is guided by a uniform magnetic field ($B \sim 10$ kG) down a smooth cylindrical waveguide (no FEL pump). This radiation, which grows in

amplitude with distance traversed, is probably generated by the cyclotron maser (gyrotron) instability, and would thus be an indication of transverse energy in the beam electrons.

Experiments are under way to study the power and frequency characteristics of millimeter wave (λ = 1-10 mm) radiation generated by a high-current electron beam propagating in a 1.9-cm diameter cylindrical stainless steel pipe. The REB diode is energized by a Physics International Pulserad 110-A electron-beam generator capable of delivering 20 kA of current at 1.5 MV. Both the pipe and the diode region are immersed in the uniform axial magnetic field of a 1-m-long solenoid.

We compare microwave power and spectra from beams produced in two diode configurations: foilless and with anode foil. In each case, the dependence of microwave emission on beam current, anode-cathode gap spacing, cathode shape, and (when applicable) foil thickness is investigated. Titanium foils, 0.5, 1 and 2 mils thick, have been used. In addition, limiting apertures placed between the diode and the pipe have been used to collect up to 90% of the beam current, allowing us to study microwave emission from the inner portion of the beam. In this way we are able to eliminate electrons emitted from the cathode edge where the diode electric field is not oriented parallel to the guiding magnetic field. Current measurements made with a series of such apertures also allow us to estimate the radial current-density profile in the beam under different diode conditions.

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c. Electrically Pumped, Relativistic, Free-Electron Wave Generation

Stimulated scattering induced by the longitudinal electric field of a pump wave is studied theoretically for the case of dense, relativistic electron beams traveling in cylindrical metal waveguides. Two processes are examined. In one, the pump wave decays parametrically into a slow and a fast space-charge wave. In the other, it decays into a slow space-charge wave and a TM wave of the guide. The dispersion

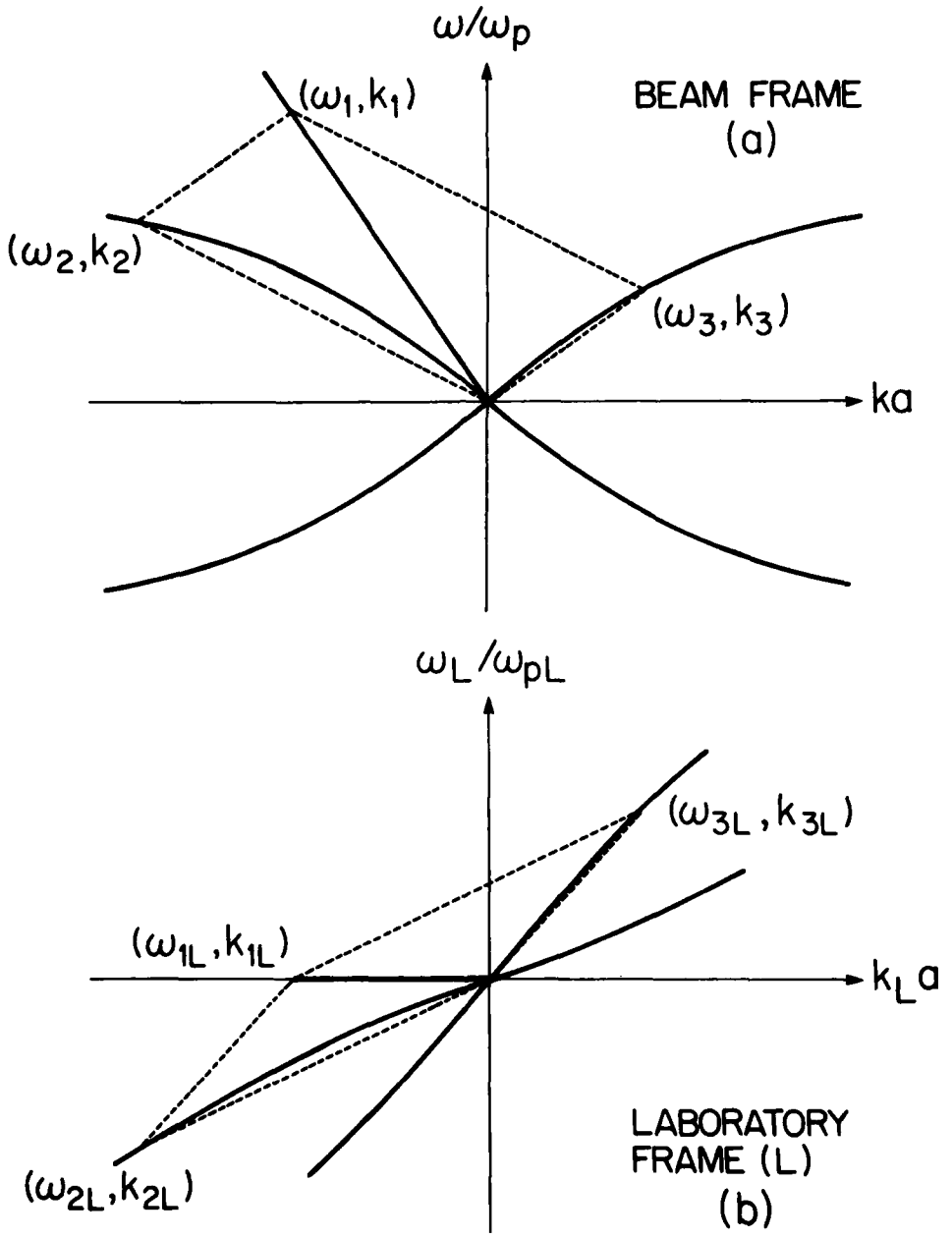

Fig. XX-2a. Schematic dispersion diagrams illustrating the coupling between a static pump wave (1), a slow space-charge wave (2), and a fast space-charge wave (3), as observed in the beam frame (top) and the laboratory frame (bottom). For clarity, the two figures are drawn to different scales.

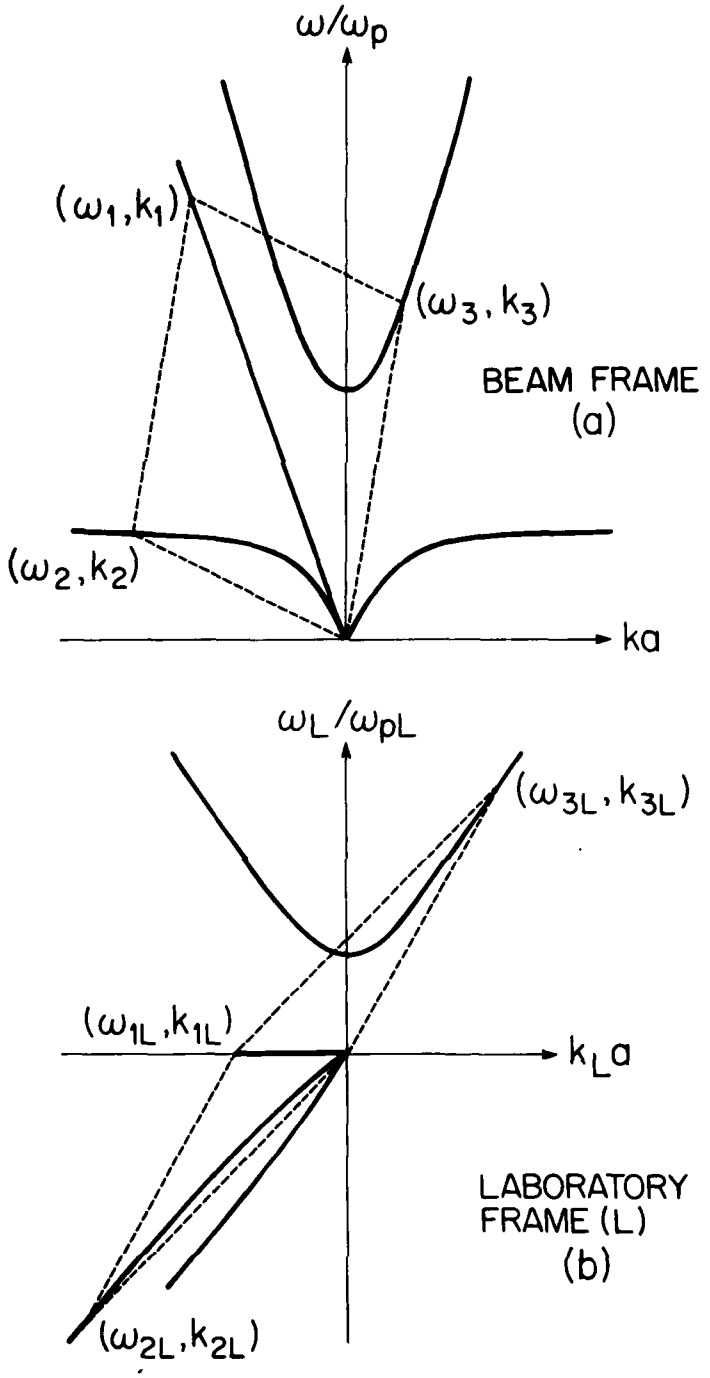

Fig. XX-2b. Schematic dispersion diagrams illustrating the coupling between a static pump wave (1), a slow space-charge wave (2), and a TM mode (3) of the waveguide, as observed in the beam frame (top), and the laboratory frame (bottom). For clarity, the two figures are drawn to different scales.

diagrams in Figs. XX-2a and XX-2b illustrate the two processes. The frequency characteristics and stimulated growth rates have been calculated for each process, as a function of beam diameter, velocity, and density.

d. Experiments and Computer Simulation of Relativistic Magnetrons

Experiments are in progress on the six-vane relativistic magnetron[1] operated in the 2π mode[2] at voltages in the range of 0.8-1.5 MeV. The microwave power is extracted from a single resonator through an iris-coupled waveguide; however, dummy loads are placed on the remaining resonators in order to insure uniform cavity loading and field symmetry.[3] Power spectra have been measured for a variety of field-emission cathode configurations.

A two-and-one-half-dimensional, electromagnetic, computer-simulation code has been tested on a coaxial relativistic magnetron[4] operating in the π mode. The code is coupled to an external lumped circuit simulating the voltage supply. The time evolution of the rf field is illustrated in the left-hand side of Fig. XX-3. Initially, an external "priming" field is imposed in order to speed up the time to saturation, which occurs after $\sim$8 nsec. The right-hand side of Fig. XX-3 shows the charged-particle distribution at saturation (time = 15 nsec), clearly illustrating the formation of a space-charge spoke.

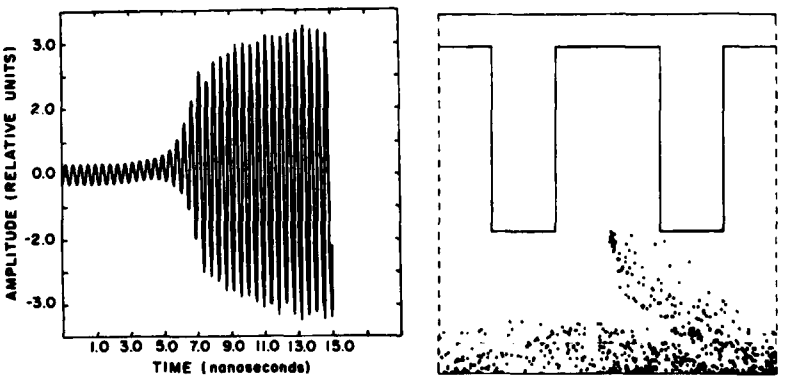

Fig. XX-3.

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XX. PLASMA DYNAMICS

B. Plasma Research Related to Fusion

1. PHYSICS OF THERMONUCLEAR PLASMAS

U.S. Department of Energy (Contracts DE-AC02-78ET51013
and DE-AS02-78ET53073.A002)

Bruno Coppi

An understanding of the physics of high-temperature plasmas is of primary importance in the solution of the problem of controlled thermonuclear fusion. One of our goals is the magnetic confinement and heating of plasmas with densities in the interval 10^{14} to 10^{15} particles/cm^3 and thermal energies in the few kiloelectron-volt range. The macroscopic transport properties (e.g., particle diffusion and thermal conductivity) of plasmas in these regimes are weakly affected by two-body collisions between particles. The relevant transport coefficients, in fact, are influenced significantly by the type of collective modes that can be excited, such as density and temperature fluctuations caused by microinstabilities.

The primary focus of our activities has been on the experimental effort involving the Alcator A and C devices. Our purpose has been to realize plasmas that can sustain very high current densities without becoming macroscopically unstable, in order to achieve the highest possible rate of resistive heating of the plasma and relatively high density regimes.

Alcator's unique properties, high current and particle densities and relatively low impurity concentration, have made it one of the most successful confinements in terms of achieving the highest known values of the confinement parameter "$n\tau$," of producing for the first time near impurity-free plasmas of thermonuclear interest, and of realizing a sequence of plasma regimes of basic physical interest.

In particular, during 1979, experiments on the injection of microwaves at the lower hybrid frequency, which for the system adopted on Alcator A is 2.45 GHz, have been undertaken systematically at power levels of approximately 100 kW. One of the most striking observable effects has been the enhancement of the rate of fusion-neutron emission in deuterium plasmas, by approximately a factor of 30 when compared to the case where there is no injection of microwave power. Therefore it has

been possible to verify the dependence of microwave penetration and energy deposition on different macroscopic parameters, such as the magnetic field, the particle density, and the plasma current.

The Alcator C device has been brought to regular operation with well-confined plasmas and plasma currents of approximately as high as 300 kA. We recall that the reference design value of the total plasma current is 1 megampere and that one of the objectives of Alcator C is to achieve values of the confinement parameter $n\tau$ around 10^{14} sec/cm^3.

A major program on microwave heating of Alcator C has been developed with the goal of realizing a system for injection of up to 4 megawatts at a frequency of 4.6 GHz. This is in the range of the lower hybrid frequency for the values of the plasma density that are expected to be realized. A parallel program of heating at the ion cyclotron frequency has also been undertaken and a series of relevant experiments has been prepared to be carried out on the Alcator A device. The objectives of these efforts are to be able to raise the maximum temperature of plasmas with peak densities of approximately 10^{15} particle/cm^3 above 2 keV and to study their basic confinement properties in conditions where the effectiveness of ohmic heating begins to degrade. The experimental program is integrated with a theoretical effort for the numerical simulation of the plasma regimes that we hope to obtain.

The analysis of a relatively large variety of experiments (including among others the Alcator A and C, the Frascati Torus and the Princeton Large Torus where the most interesting plasma regimes have been obtained) has allowed us to formulate analytically a transport model which reproduces consistently the electron-density profile, the electron-energy confinement time, and the particle-density profiles that have been observed experimentally over a wide range of conditions.

This model that presupposes the excitation of microscopic plasma collective modes arrives at the identification of the relevant transport coefficients for the electron thermal energy and the particle density on the basis of global conditions involving particle and energy balance, criteria for the macroscopic stability of the plasma column, etc. This has strengthened the basis for the transport model and the codes that have been developed as part of our program, and that have been used both to predict the performance of Alcator C and to formulate a research program on ignition experiments by a series of compact devices. These are generally called Ignitors

or Alphators, and represent the natural evolution of the Alcator program into a generation of high-particle-density, relatively small-dimension fusion reactors. A design study of an Alcator D device along the same line has been undertaken.

Other theoretical achievements involve the identification and the analysis of new regions of stability, in the relevant parameter space, for magnetically confined toroidal plasmas with plasma pressure comparable to the effective magnetic-field pressure that are of importance for the possible realization of net power-producing fusion reactors. Another area where noticeable progress has been made is in the investigation of collective modes that can produce a change of topology (so-called magnetic reconnection) in the magnetic-confinement configuration. Modes of this type are of considerable interest also for space and astrophysics.

The Rector experiment, which was originally developed to study the confinement properties of toroidal plasmas with elongated cross sections, was employed to obtain remarkable results, in terms of improved equilibrium and stability conditions, by converting its basic axisymmetric magnetic configuration into a Stellarator-like configuration with helical symmetry. A novel distribution of coils has been adopted for this and, given its favorable construction characteristics, a series of higher performance relevant experiments is being considered.

As is traditional with our mode of operation, we have maintained a system of close collaborations with national and overseas institutions for both our theoretical and experimental programs. Our contributions have been presented at major and international meetings.

2. DYNAMICS OF TOROIDAL DISCHARGES

U.S. Department of Energy (Contract ET-78-S-02-4682)

James E. McCune, Daniel E. Hastings, George M. Svolos

a. Drift Modes in Tori

James E. McCune, George M. Svolos

This work focuses on the analysis of drift and related low-frequency electrostatic (low-β) modes, in the "collisionless" and low-collisionality (banana) regime of large toroidal systems.

In our approach we make use of a drift kinetic equation with appropriate choices of the relevant parameters of the problem, and we keep finite Larmor radius and toroidal geometry effects from the outset.

In the linear treatment of the problem we abandon the traditional local approximation. Instead, we attempt an assessment of the stability properties of the system from the properties of the dispersion relation differential equation. We try to be as general as is analytically tractable in our treatment of this equation and we pay special attention to the effects of temperature gradients, the shear and the toroidal features of the magnetic field on the stability and localization properties of the modes and on the cross-flux eigenvalue problem. We also solve the dispersion relation analytically using a method of asymptotic matching. The solution and the eigenvalues so obtained, although approximate in this treatment, bear the qualitative features expected from the analysis of the dispersion relation differential equation.

In addition, we consider nonlinear turbulent electron behavior. We will examine the effects that nonlinear stochastic cross-flux electron diffusion, close to the mode rational surfaces, may have on the properties and ultimate nonlinear development of the modes.

b. Drift Modes in Tandem Mirror Systems

Daniel E. Hastings, James E. McCune

The linear theory of low-frequency drift wave is well understood in a low-β (where $\beta = 8\pi p/B^2$) plasma. However, in new experiments like the TMX, the plasma β is expected to be O(1). This represents a significant change to the physics of drift waves. In the Ph.D. thesis of Hastings we present an analysis of the physics of two prototypical drift waves when $\beta = O(1)$. First, we derive the low-frequency dispersion relation with all high-β effects included. These fall into three categories: effects due to perpendicular magnetic fluctuations, effects due to parallel magnetic fluctuations, and effects due to ∇B drifting particles. We reduce the dispersion relation to a form suitable for numerical analysis by finding a basis set of functions in which the dispersion relation can be easily expressed.

The dispersion relation is specialized to the well-known universal drift

instability. We examine the effect of each piece of high-β physics on the universal drift wave and then bring them all together. In particular, for the ∇B effects we find an analytical bound on the validity of the nonresonant approximation, and we show that it breaks down for small values of β, a result that had only previously been shown numerically. We show that universal's high-β behavior differs considerably from the electrostatic understanding. For most plasma and wave parameters, we find that the universal mode is stabilized by enhanced ion Landau damping, the enhancement arising from the reduction of the parallel phase velocity due to ∇B effects. For small β, we find that the behavior of the wave for the most part is dominated by the coupling to the Alfven wave. For large β, the behavior of the wave is dominated by the compression of the plasma flow induced by the ∇B particle drift. We find that, in contrast to the electrostatic case, the most unstable waves occur for phase velocities close to the ion thermal velocity, for long perpendicular wavelengths and for positive electron-temperature gradients. Also, we find that the high-β behavior of the wave is largely independent of the electron-to-ion temperature ratio. Finally, we compute some marginal stability curves and show that for electron-temperature gradients which are less than or equal to zero the universal drift wave is stabilized at a β_i of 0.07. For positive electron-temperature gradients, we show that a β_i of at least 0.44 is needed. The difference between the two regimes we ascribe to enhanced inverse transit-time damping for positive electron-temperature gradients.

We also examine the high-β behavior of the drift Alfven mode, and we show that when temperature gradients can be ignored the behavior of the mode for all β retains its compressionless character. We find that the mode always approaches marginal stability as β increases. However, temperature gradients change the mode behavior considerably. Electron-temperature gradients are found to be destabilizing at high β through their influence on the resonant energy transfer. Ion-temperature gradients cause a marked upshift in the oscillation frequency of the mode, and hence are strongly stabilizing.

We conclude that at high β, the Alfven mode will be stable and the universal mode may have a window of instability at long parallel and perpendicular wavelengths and positive electron-temperature gradients.

3. RF HEATING AND NONLINEAR WAVES IN TOROIDAL PLASMAS

U.S. Department of Energy (Contract ET-78-S-02-4682)

Abraham Bers, Robert H. Berman, Vladimir Fuchs, Kwok C. Ko, Vladimir B. Krapchev, Leo P. Harten, Abhay K. Ram, Kim S. Theilhaber, Maria Elena Villalon

The general objective is to explore the use of external applied rf power for the supplementary heating and confining of toroidal plasmas. Particular studies are being carried out to determine the heating and steady-state current drive with microwave power in the lower hybrid range of frequencies. The results are applied to current experiments on Alcator C and Versator II, as well as to experiments in the near future on Alcator C.

a. Current Generation by Large-Amplitude Waves

RF power has the potential to continuously generate the confining current in a tokamak plasma. The exploration of these ideas was initiated within this group a few years ago. Since then we have actively participated in workshop studies.[1-3] Our theoretical efforts in this area have turned to understanding the full nonlinear dynamics of the plasma in large-amplitude fields. For a strongly magnetized plasma the one-dimensional Vlasov distribution function has been found to all orders in the field amplitude.[4-7] The lower hybrid-driven steady-state current has been calculated and the results have been applied to current experiments on Versator II.[8]

b. Studies in RF Heating to Ignition

It is well known that the plasma equilibrium near ignition is thermally unstable. We have initiated a study to explore the advantages of using rf supplementary heating in reaching ignition. Specifically, the applied rf can be varied in time, and the potential for controlling the radial deposition of the power in the plasma also exists. We chose to study the plasma parameters of the High-Field Compact Tokamak Reactor (HFCTR).[9] We have studied the global[10] and radial[11] equilibria. The low-temperature (7-20 keV) equilibrium is unstable, but can be stabilized by a programmed rf heating source, which is gradually turned off near equilibrium.

c. Nonlinear Effects in Coupling of RF Power to a Plasma

For LH heating the nonlinear effects are prominent in the low-density and temperature region of the plasma edge. These effects have been seen experimentally over the past two years. We have proposed a nonlinear equation, which describes the nonlinear coupling of LH waves.[12] The Vlasov theory of spatially modulated waves[4-7] confirms this result. During the past year the analytical model was refined so that the nonlinear coupling problem could be solved in some detail. For a two-waveguide array, an approximate analytical solution was found. It exhibits the reduced dependence upon waveguide phasing and shows an upshift in the $n_{||}$-spectrum, both consistent with experimental observations.[13] We have initiated two numerical schemes for solving the nonlinear equation; one attempts to find a steady-state solution for the fields, the other studies the time evolution of the coupling.

d. Linear Propagation, Mode Conversion, and Damping in Inhomogeneous Toroidal Plasmas

A *full electrostatic, local* dispersion relation[14] is used to numerically study the propagation characteristics of waves near the LH frequency in an inhomogeneous plasma ($\nabla n, \nabla B, \nabla T$). For relevant tokamak parameters and profiles, the results show significant differences from those previously obtained.[15] The linear mode-conversion process from LH to warm plasma wave is downshifted to lower $n_{||}$, and is confined spatially to regions in between the ion-cyclotron harmonics.

e. Parametric Excitation in Lower-Hybrid Heating of Tokamak Plasmas

We have carried out a detailed linear and nonlinear analysis of quasimode type of parametric excitations relevant to the recent Alcator A heating experiment.[16] This quasimode excitation has been studied independently for the regions near the edge and the center of the plasma. The analysis near the edge shows that higher n_z's than predicted by linear theory are strongly excited, which may prevent the penetration of the rf power to the plasma center. Inside the plasma the power density is much lower than at the edge and is no longer confined to well-defined resonance cones; it is spread out across the plasma column.

Currently, we are in the process of evaluating the importance of resonant parametric excitations and contrasting them with the quasimode excitations.[17]

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4. NONLINEAR THEORY OF TRAPPED-PARTICLE INSTABILITIES

U.S. Department of Energy (Contract DE-AS02-78ET53074)

Thomas H. Dupree, David J. Tetreault

The phenomenon of clumps is being studied in a plasma with a magnetic field. In particular, the effect of clumps on the drift and trapped-particle mode instabilities is being studied. Clumps in the ion phase-space density produce an enhanced ion viscosity which appears to be very effective in damping these modes and providing a nonlinear stabilization.

Concepts from strong plasma turbulence are being used to investigate magnetic islands in tokamaks. Turbulent magnetic fluctuations induced by drift waves as well as those formed through self-consistent currents are being studied. The purpose is to determine how the resulting turbulent destruction of magnetic surfaces affects tokamak plasma confinement.

Work is also beginning on computer simulations of the structure of clumps in plasma.

5. AN ADVANCED SCIENTIFIC COMPUTING ENVIRONMENT

National Science Foundation (Grant ENG79-07047)

Robert H. Berman, Thomas H. Dupree, John L. Kulp, Jr.

Several problems in plasma dynamics concerning microturbulence and nonlinear phase-space structures[1,2] can be studied experimentally only by computer simulation techniques. These studies are essential to complement the theoretical studies that have been described in previous sections. These simulations for clumps, for example, require a fully kinetic, self-consistent description of the particles with high resolution in phase space that can represent discrete particle effects. Very effective algorithms have been developed to study these problems that will promote very efficient and cost-effective computer simulations.[3,4] The macrocell algorithm as originally envisioned will promote very accurate determination of short-range interparticle forces and, therefore, permit longer, more precise situations before numerical

errors grow beyond reasonable bounds.

Our efforts to create an advanced scientific computing environment consisting of a LISP machine and array processor that supports interactive symbolic and numerical calculations are well under way.[5,6] The core of this project is the high-performance personal computer consisting of a LISP machine coupled with an arithmetic processor capable of a raw computing rate of ≈10 million floating-point (numerical) operations per second.

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6. TOKAMAK RESEARCH: RF HEATING AND CURRENT DRIVE

U.S. Department of Energy (Contract DE-AS02-78ET53050)

George Bekefi, Miklos Porkolab, Kuo-in Chen, Stanley C. Luckhardt

Introduction

The use of rf power near the lower hybrid frequency has long been considered as a means of heating ions in tokamak discharges.[1,2] More recently, experiments have shown that electron heating can also be obtained from lower hybrid wave injection.[3] In view of the apparent capability to modify the electron velocity distribution function by injection of a properly tailored wavelength spectrum of lower hybrid

waves, it has been recently proposed that lower hybrid power injected with a net toroidal angular momentum should be capable of producing, via Landau damping, a steady-state toroidal current in tokamaks.[4] A fusion reactor driven in steady state with rf power has a number of attractive features distinguishing it from the commonly encountered transformer-driven pulsed machines. Lower hybrid experiments in progress on Versator II using phased-waveguide array, grill-type coupling structures are capable of studying all three aspects of current interest in the lower hybrid frequency range: ion heating, electron heating, and current drive.

In a second series of experiments to begin in mid 1980, microwave power will be injected into Versator II at the electron-cyclotron frequency. For this purpose, the newly developed gyrotron microwave source will be provided along with scientific and technical support from the Naval Research Laboratory. The NRL gyrotron will allow ECRH experiments to be carried out at significant power levels in the range of 100-120 kW at a frequency of 36 GHz.

To obtain a quantitative physics understanding of rf processes in tokamak plasmas, the target plasma must be capable of a well-controlled and flexible equilibrium state, and energy confinement and transport processes must be carefully monitored with a full array of tokamak plasma diagnostics. For this reason, a major effort is under way at Versator to implement a full range of plasma diagnostic experiments; and the plasma equilibrium and operation is being carefully studied and documented to provide a reliable benchmark for ongoing rf experiments.

Equilibrium Studies and Diagnostics

Equilibrium of the Versator II plasma is characterized[5] by plasma currents in the range of 30-50 kA, central density of 2×10^{13} cm^{-3}, toroidal field of 10-15 kgauss, major radius 40 cm, minor radius 13 cm, and flattop current pulse durations in normal operation in the range of 20-40 msec. Constant horizontal and vertical plasma positions needed for the rf experiments have been obtained with deviations not exceeding 0.5 cm. Low plasma impurity levels are indicated by the rapid density decay after initiation of the discharge.

Plasma density has been increased to 4.5×10^{13} cm^{-3} and sustained for a few milliseconds by gas puffing with consistent measurements with both 4-mm and 2-mm

microwave interferometers. Extensive measurements of the density in the region between the edge of the plasma and the lower hybrid antenna structure have been made with Langmuir probes. The density is found to follow an exponential dependence in the edge region, and the density gradients in the region of the grill are found to be in the range of 10^{10} to 10^{11} cm^{-4} depending on the grill location.

Electron temperature during rf heating experiments is being monitored by a ruby laser Thomson-scattering system and supplemented by spectroscopic measurements in the ultraviolet, of impurity-line spatial profiles. Thomson-scattering temperature measurements indicate central electron temperatures in the range of 400-600 eV which is consistent with the observed relative intensities of the impurity lines O VII 1623 Å, N VI 1897 Å, CV 2271 Å, O V 2781 Å, and NV 1239 Å. In addition, two heterodyne detectors for observing fundamental and 2nd-harmonic cyclotron radiation are available for time-resolved, semiquantitative electron-temperature measurements.

The high-energy ion tail generated during lower hybrid heating is expected to be well confined in Versator in view of the small field ripple, $\Delta B_T/B_T \lesssim 2 \times 10^{-3}$ on axis; thus not only tail generation but bulk ion heating as well may be observed. The presence of the ion tail will be monitored by a neutral charge-exchange system, and bulk ion temperature by impurity atom spectral-line Doppler widths using an ultraviolet spectrometer.

Microwave scattering experiments have been carried out in the Versator II plasma with approximately 5 watts of power at 140 GHz.[6] Reliable measurements were obtained after installation of refractory microwave-absorbing material in the tokamak vacuum vessel in the region around the microwave horns. Measurements in this configuration show a spectrum of density fluctuations which is monotonically decreasing with ω for all values of $k_\perp$, with fluctuation activity in the drift-wave frequency range up to 300 kHz. This detector will be used to scatter from density perturbations associated with propagation of the high-power lower hybrid waves in the plasma during the heating and current-drive experiments.

RF Experiments

A lower hybrid antenna system operating at 800 MHz with peak power levels of $P \sim 150$ kW has been constructed on Versator.[7] This system, shown in the schematic diagram in Fig. XX-4, has the flexibility to employ a four-waveguide grill designed

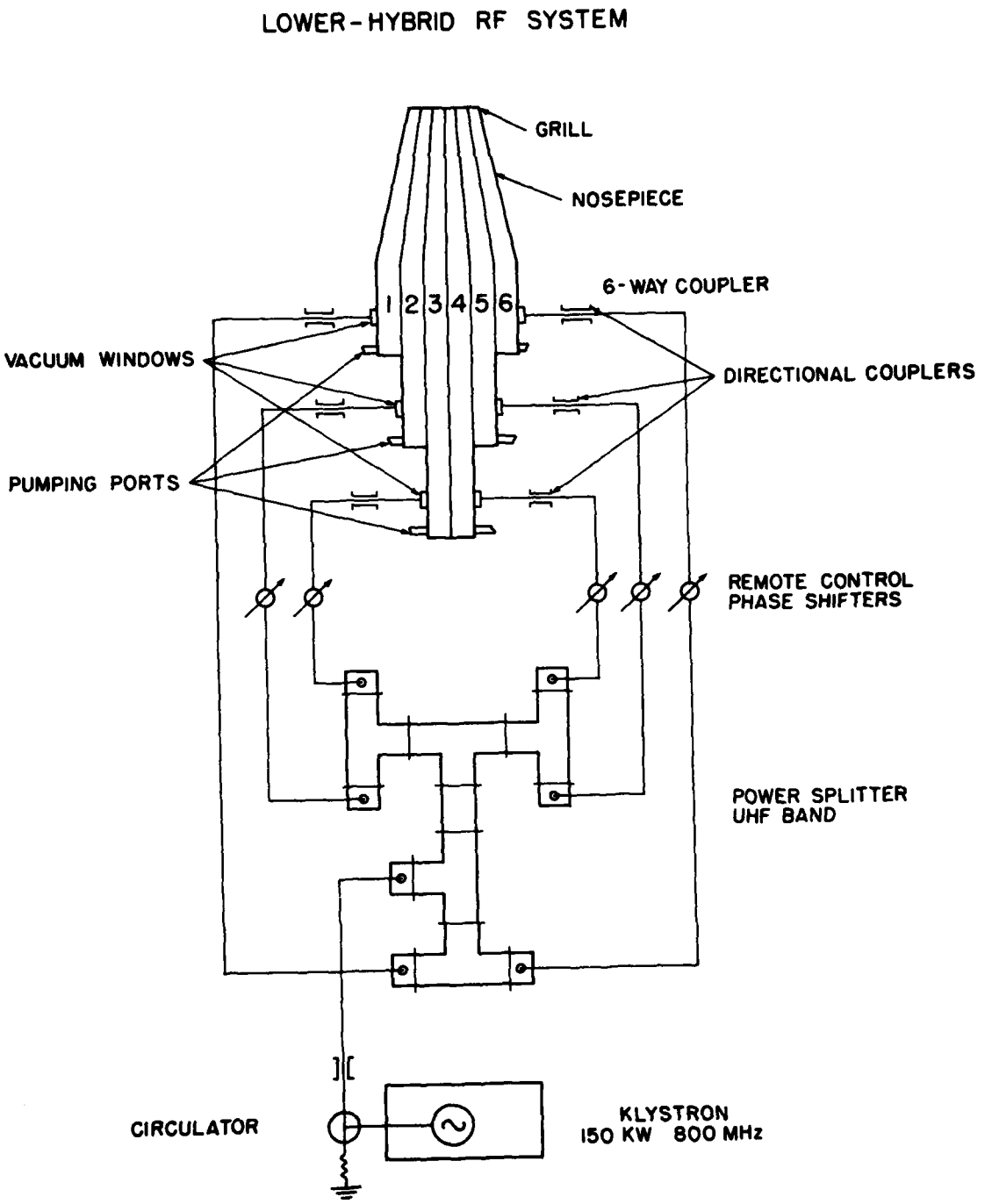

Fig. XX-4. RF system.

to produce a power spectrum favorable for ion heating studies, or a six-waveguide grill for electron-heating or current-generation studies. The rf system consists of a coaxial-fed, vacuum-pumped waveguide array with a tapered, interchangeable "nose-piece" section which is inserted into the tokamak vacuum vessel. The system can be used with both four- and six-waveguide grills, and the relative phases, ϕ, between adjacent waveguides are continuously adjustable. These features of the MIT RF system allow a wide range of lower hybrid power spectra to be produced either for ion or electron heating, or the unidirectional power spectrum desired for current-generation experiments.

To date, measurements of RF coupling to the plasma have been carried out in some detail. At the relatively low power levels investigated, P = 0.5-10 kW, S = 1-20 W/cm^2, the coupling efficiency is found to be strongly dependent on the relative phase of the waveguides and the position of the grill relative to the plasma limiter. In the four-waveguide experiment, minimum total-power reflectivities obtained are R = 17% with guide phasing in the range of ϕ = 90°-180°. As shown in Fig. XX-5, optimal coupling was obtained by positioning the grill 3.1 cm behind

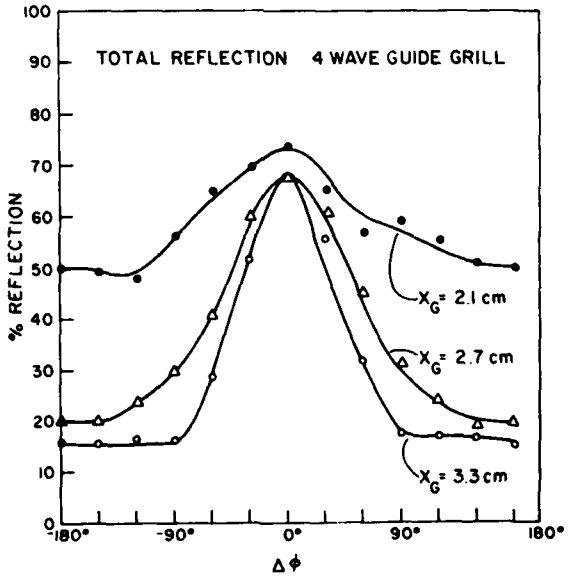

Fig. XX-5. Experimentally observed coupling (4-waveguide grill).

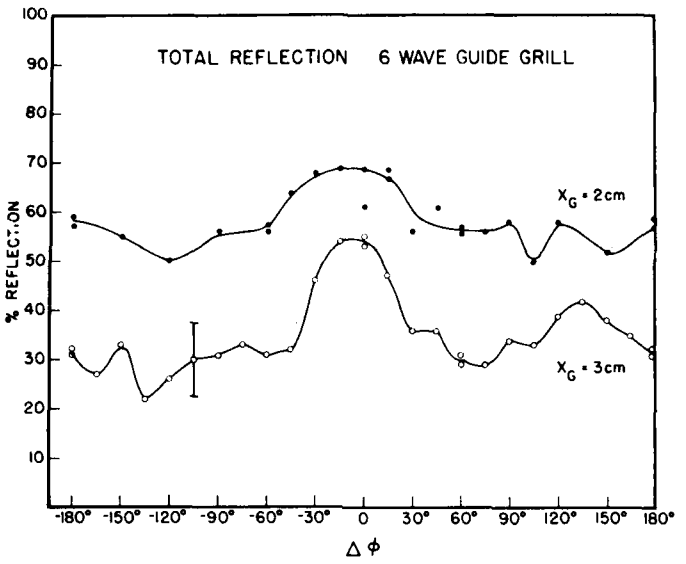

Fig. XX-6. Experimentally observed coupling (6-waveguide grill).

the limiter. In six-waveguide experiments, optimized total reflections of R = 25-35% are obtained with the grill located 3 cm behind the limiter, as shown in Fig. XX-6.

For comparison with the waveguide-coupling theory, the density profile in the region between the limiter and the grill mouth has been measured with Langmuir probes, yielding the parameter ∇n needed in the Brambilla waveguide-coupling theory.[2] The observed density gradients at the waveguide mouth are typically in the range of 10^{10} to 10^{11} cm^{-4} depending on the grill location. For such density gradients, waveguide-coupling theory predicts total reflectivities of R = 75-80% for the six-waveguide grill; thus the observed coupling is much better than the theoretical expectation. If density gradients 10-100 times larger than those measured are assumed, the theory yields semiquantitative agreement with the observations. This result, that agreement is obtained by assuming a large value of ∇n, has been found in other experiments;[8,9] however, in those works independent measurement of ∇n was not made, so our experiments are the first where such a discrepancy between the theory and experiment is documented.

In the coupling experiments, low power levels were used, S = 1-20W/cm^2, so that

nonlinear effects are probably unimportant in explaining the discrepancy between theory and experiment. However, a number of improvements are suggested in the linear theory by the present experiments. A more realistic theory should contain boundary conditions, including the details of the tokamak port conducting wall shape, density gradients in the direction parallel to the magnetic field which have been observed in our experiment, the finite height of the waveguides, and the experimentally measured density profiles.

At high rf power levels, P = 100 kW, current-drive experiments with the six-waveguide grill are predicted by recent transport code calculations[10] to produce an additional toroidal current in Versator of ΔI = 20 kA (initial conditions T_{eo} = 300 eV, $n_0 = 2 \times 10^{13}$ cm^{-3}, and I_p = 40 kA). Production of an rf-driven toroidal current in an ohmically heated toroidal discharge is also expected to produce a strong runaway electron component; so, in addition to electron temperature-measurements, a hard x-ray monitor is employed to detect the rf-produced high-energy runaway activity.

The high-energy ion tail generated during lower hybrid ion-heating experiments (4-waveguide grill) is expected to be well confined in Versator, in view of the small toroidal field ripple, $\Delta B_T/B_T = 2 \times 10^{-3}$ on axis; thus, bulk ion heating is also expected.

Experimentation in 1980 will concentrate on raising the rf power levels coupled into the plasma so that significant heating and current generation can be observed.

Klystron and power supplies on loan from Princeton Plasma Physics Laboratory.

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7. MIRROR-CONFINED PLASMAS

U.S. Department of Energy (Contracts DE-AS02-78ET51002 and DE-AS02-78ET53076)

Louis D. Smullin, Robert E. Klinkowstein

We are studying problems related to the physics of plasma confined in min-B magnetic mirrors. The system Constance II has a mirror field of 2:1 ratio, with a maximum value of $B_{max} \approx 10$ kG. A quadrupole coil mounted in the vacuum system, and excited by a capacitor bank, can produce a full min-B field configuration when the midplane field is 3 kG.

The facility was completed by December 1979, and we have been making detailed measurements of the plasma characteristics. Diagnostics now in place include: 4-mm interferometer, neutral-particle energy analyzer, vacuum-ultraviolet monochromator, probes, diamagnetic coils, and various probes. A Thomson-scattering laser system is under construction.

In the smaller facility, Constance I, we are studying the behavior of the "washer plasma gun." We have built a fast-acting (msec) gas valve for the 2-inch washer gun, and we are comparing the behavior of two guns: one using an H_2-saturated Ti washer, and the other with controlled, pulsed gas injection.

The behavior of the magnetron injection gun, used for beam-plasma interaction, is being studied with the help of a computer-simulation code. A program, originally developed at SLAC, for plotting electron trajectories in guns with very weak space charge, has been modified to handle full space charge of guns with perveance as high as 15×10^{-6} volts/amp$^{3/2}$.

COMMUNICATION SCIENCES

AND

ENGINEERING

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XXI. OPTICAL PROPAGATION AND COMMUNICATION

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The broad objectives of our program are to (i) formulate propagation models for important optical channels from the underlying physical processes, (ii) determine the fundamental limits on detection and communication performance that can be realized with these channels, (iii) develop techniques for optical detection and communication which achieve or approach these limits, and (iv) establish, by means of experiment, the validity of the theoretical results and guide their further development.

1. IMPROVED LOW-VISIBILITY COMMUNICATION

National Science Foundation (Grant ENG78-21603)
U.S. Army Research Office – Durham (Contract DAAG29-80-C-0010)

Robert S. Kennedy, Jeffrey H. Shapiro, Cardinal Warde

This investigation, part of which is carried out jointly with the MIT Center for Materials Science and Engineering, is concerned with the performance of terrestrial communication systems under conditions of low visibility. Our goal is to determine the extent to which the performance can be improved through the appropriate system design, and to develop the devices for achieving this improvement. The potential for improvement resides in the energy and information contained in the scattered component of the received field.

This year has seen the beginning of a gradual shift from exploratory propagation measurements on atmospheric channels to the development of appropriate theories to

predict the behavior of such channels. This transition had previously been precluded by the absence of both sufficient information on the approximate magnitudes of the important effects and also an adequate data base against which to check the models.

Two approaches to the modeling problem are now being actively pursued. In one the salient features of our experimental results are being used to suggest useful approximations to the transport equation.[1] One particularly promising approximation is suggested by the observation that, in the situations of interest, the scattered field is relatively insensitive to the spatial inhomogeneities of the medium. This implies that the source term in the transport equation can be neglected. The second approach has been to apply several available models to our experimental situations and compare the predicted behavior with the experimental observations. To date, models based upon single scatter, multiple forward scatter, and diffusion have been examined.[1-5] For the optical thicknesses that have been considered, the multiple-forward-scatter model is the best of the three but is not entirely satisfactory. In an attempt to obtain better results, the multiple forward scatter and diffusion approximations are now being combined in one model.

Although our previous experimental work has yielded enough data for the analytical modeling effort to begin this year, more data at shorter wavelengths and at the shorter ranges contemplated for a projected communication system were needed. Accordingly, we have continued to collect data at wavelengths of 0.53 μm and 0.25 μm.[6] Also, a new off-campus laboratory located approximately 6 km from the campus laboratory has been put into operation.

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2. QUANTUM COMMUNICATION THEORY

Joint Services Electronics Program (Contract DAAG29-78-C-0020)

Horace P.H. Yuen, Jeffrey H. Shapiro, Robert S. Kennedy

The long-range goal of this investigation is to realize improved optical communication, detection, and estimation in the space environment. Such improvement may be possible through the use of quantum measurements (optical receivers) that are superior to those now considered and the use of quantum states other than coherent states.

During the past year it has been shown that, for digital communication with error probability as a performance measure, the optimum quantum receiver for either pure coherent states or pure two-photon coherent states is not markedly superior to the performance that can be achieved with homodyning.[1] This resolves a question that has persisted for some time and brings our work on that issue to a close. Our other work pertains to the propagation of quantum states and the potential benefits that can accrue from using two-photon states. These issues have been addressed in a series of papers[2-4] which provide a fundamental understanding of the statistical properties of these states and a potentially practical means of generating them. In addition, the way in which their use could significantly improve the capacity of fiber data networks has been recognized and analyzed.[5]

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XXII. DIGITAL SIGNAL PROCESSING

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The Digital Signal Processing Group is carrying out research in the general area of digital signal processing with applications to speech, image, and geophysical data processing. In addition to specific projects being carried out on campus, there is close interaction both with Lincoln Laboratory and with the Woods Hole Oceanographic Institution.

In the area of speech processing, over the past several years the Digital Signal Processing Group has been working on the development of systems for bandwidth compression of speech, parametric modeling of speech using pole-zero models, and enhancement of degraded speech. Our work in the speech area is currently heading toward an increasing involvement with the problem of enhancing degraded speech and a related problem, that of the development of algorithms for robust speech compression in the presence of additive noise.

In a related area the methods of speech compression using linear predictive encoding are being applied to the compression of data recorded in ocean-bottom seismometers. These methods are being tested with data provided by the Woods Hole Oceanographic Institution.

The areas of image and geophysical data processing in general both involve the processing of multidimensional signals. The theoretical projects in 2-D signal processing include filter design (e.g., 2-D all-pass design to match phase

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response), the synthesis of good 2-D filter implementations, 2-D spectrum analysis, and 2-D deconvolution. We have been pursuing a number of projects specifically related to geophysical data processing. We are applying some of the filter design results to seismic-wave migration by implementing a program on our MAP processor. Another project, which has been carried out in collaboration with the Woods Hole Oceanographic Institution, is the development of an algorithm for data processing to measure the acoustic reflection coeffcient from the ocean bottom. Out of this work has come a Hankel transform algorithm which has potential applications to a number of other problems. Another problem area is that of velocity analysis on array data. The specific application that we are considering is that of velocity analysis on well logging data. We are also pursuing a number of other problems associated with the analysis of well logging data, including the development of techniques for event detection. In another application of velocity analysis, we have applied adaptive array processing to measure the reverberation of acoustic signals in the Arctic Ocean, as well as the phase velocity of the seismic paths within the seabed. Acoustic imaging from a submersible often generates an image dominated by strong highlights because of the specular reflections introduced by the relatively long wavelengths. We are working on an adaptive array processing method to suppress the deleterious effects of these highlights in the image.

There are also a number of projects related to image processing that we are currently pursuing. With regard to the problem of image restoration/enhancement, we have developed a new image restoration system which is effective in reducing various image degradations such as additive noise, multiplicative noise, blurring, etc. This image restoration system has also been applied with successful results in reducing quantization noise in PCM image coding. With regard to the problem of phase-only image reconstruction, we have several theoretical conditions under which an image can be exactly recovered within a scaling factor only from its phase function. In addition, numerical algorithms have also been developed to perform image reconstruction from its phase. These results have the potential for significant impact on various image processing problems such as image coding, image registration, etc.

In both the context of image processing and array processing, we are also exploring such topics as high resolution, multidimensional spectral estimation,

and two-dimensional short-space signal processing. The work on image processing is being carried out in collaboration with Lincoln Laboratory.

1. LINEAR PREDICTIVE ENCODING OF SEISMIC DATA

U.S. Navy – Office of Naval Research (Contract N00014-75-C-0852)
National Science Foundation Fellowship

Thomas E. Bordley, Arthur B. Baggeroer

In studying the earth beneath the ocean floor, the use of ocean-bottom sensors physically isolated from the controlling research vessel offers many advantages over the use of surface sensors or deep-sea arrays. Per se, since the sensor is in contact with the bottom, the complex effects associated with the passage of a signal across the earth-water interface and through the sea are eliminated. Furthermore, because the signals are observed in the earth, the shear and stress components of the returns can be recorded as distinct signals (through the use of horizontally and vertically polarized sonars), thus increasing the amount of information gathered. Finally, unlike free-floating deep-sea arrays, the location of an ocean-bottom sensor is secure. Thus, the difficult problem of controlling the position of an array is eliminated as well as the noise effects associated with the residual movement of the sensor.

In such work, storing data in digital form is desirable since it simplifies gain-ranging and other techniques used to ensure high quality reproduction of the observed signals. Unfortunately, at present, digital recording requires an order of magnitude more storage than analog recording. Thus, since seismic signals are of long duration and of wide dynamic range, the limited amount of storage which can be placed on the sea floor presents a severe constraint on the amount of data which can be gathered using all-digital techniques. For this reason, it is of considerable interest to develop a scheme for minimizing the amount of storage required to faithfully represent these signals. In effect, one wishes to reduce the cost associated with the digital approach by using the available storage as effectively as possible.

This research examines the effectiveness of linear predictive encoding in performing seismic data compression. This technique was selected for study originally

because of its widespread use in speech processing and general data communication. The basic idea of this technique is to pass a signal through a linear, shift-invariant, causal and causally invertible whitening filter, and then to store the filter parameters and the whitened signal instead of the original data. The term linear predictive encoding is appropriate because whitening with this filter is equivalent to subtracting from each signal point the linear least-squares prediction of the point based on previous signal values. Thus, the whitened signal is the sequence of prediction errors made by the linear least-squares prediction filter. The rationale for using this approach to achieve data compression is that if a signal is sufficiently predictable (i.e., if the energy in the error signal is sufficiently small compared to the original signal energy), then the dynamic range of the whitened signal will be significantly less than the dynamic range of the original signal. Thus, the total number of bits required to represent the whitened signal and the filter parameters will be much less than that needed to represent the waveform directly.

This work was performed on data supplied through Dr. Graham M. Purdy of the Woods Hole Oceanographic Institution.

2. EVENT DETECTION IN SONIC WELL LOGGING

National Science Foundation (Grant ENG76-24117)

Webster P. Dove, Alan V. Oppenheim

Oil wells are analyzed by acoustically testing at many places along their depth, from which a sound velocity profile can be developed. For each test a pulse of sound is generated at the bottom of a 13 meter long test probe and received at four microphones spaced at one meter intervals at the top of the probe.

The signal received at each microphone is the sum of many overlapping dispersed pulses, each of which has travelled a different path. To find the velocities in the paths of interest the arrival time of each related pulse must be determined accurately. That requires a method of reducing the dispersion of the pulses so they become distinct separate arrivals.

To do this signal processing, we are using Recursive Least Squares prediction

(the covariance method) to cancel the filtering effect of the different paths. Then the arrival time of the first and second pulses (which are the ones of interest) should be apparent either in the output of the predictor or the behavior of the predictor coefficients.

3. ADAPTIVE ARRAY PROCESSING FOR HIGH-RESOLUTION ACOUSTIC IMAGING

U.S. Navy – Office of Naval Research (Contract N00014-77-C-0257)
National Science Foundation Fellowship

Gregory L. Duckworth, Arthur B. Baggeroer

Determination of the internal structure of a medium opaque or ill-suited to electromagnetic radiation is a problem encountered in many different applications. High-resolution visualization of underwater objects through turbid seawater is the problem currently being dealt with; however, other applications include real-time viewing of internal movements of the human body without x-ray's potentially harmful effects, nondestructive testing of metallic and low x-ray contrast objects, and determination of the earth's subsurface structure.

Because of their analogous behavior to electromagnetic radiation with respect to reflection, diffraction, and refraction, but differing attenuation and physiological properties, short wavelength acoustic pressure waves can be used to perform the above tasks, but with a new set of inherent advantages and difficulties. For example, in the context of the undersea environment, acoustic imaging has an advantage over optical imaging in that the attenuation of the acoustic-pressure waves is dependent primarily on the temporal frequency, and relatively independent of the density of suspended solids, whereas light is subject to intense backscattering from cloudy water. A result of this is that the "range-to-reverberation" limit is larger for acoustic imaging, and although absorption at wavelengths adequate for reasonable resolution is high, we can theoretically increase the illuminating power and obtain the desired range capabilities.

The problems with acoustic imaging stem from the need to keep the wavelengths long enough for adequate range, SNR, and power consumption, and short enough for good resolution and small receiver apertures. These considerations ultimately lead to systems with small numerical apertures with the diffraction field under-

sampled in space and hence, poor resolution and aliasing problems. Resolution seems to be the most problematic issue since the large point-spread function generated by classical (Fresnel transform) processing is subject to tremendous amounts of sidelobe leakage from specular reflections. Typically a great deal of specularity is encountered since the illuminating wavelengths are large compared to the surface roughness of the objects to be imaged.

These problems have led us to the thrust of the current research — application of the "Maximum Likelihood" technique of spectral analysis to adaptive array processing of the diffraction-pattern samples. It has been found that the adaptive point-spread function of a system incorporating this technique yields better resolution for distributed objects as long as care is taken in estimation of the spatial-covariance function. The subtlety involves making the spatial covariance appear like it was formed by reflections from statistically independent incremental areas. The work also involved determination of the statistics of the estimators when an inadequate number of data vectors are used to ensure that the spatial-covariance matrix is distributed in a complex Wishart manner. Two-dimensional arrays that are optimized in some sense for good resolution and aliasing reduction with the minimum number of sensors are also examined.

This work was completed in September 1979 and is reported in a Master's thesis entitled, "Adaptive Array Processing for High Resolution Acoustic Imaging," by G.L. Duckworth. The results were presented at the 9th Symposium on Acoustic Imaging and Holography in December 1979.

4. DESIGN OF TWO-DIMENSIONAL FILTERS

National Science Foundation (Grant ENG76-24117)

David B. Harris, James H. McClellan

Two methods for the design of two-dimensional (2-D) rational digital filters are developed. Both methods utilize a reflection coefficient function (RCF) representation for the system function. The RCF characterization is an extension of the 1-D Levinson recursion. Its use substantially simplifies the stabilization of filters in the design process.

In one approach, the design problem is formulated as a frequency domain error norm minimization. The norm is a measure of the difference between a desired frequency response and the response of the approximating filter. In this context, the RCF representation is used to construct a set of barrier functions which augment the error so as to restrict the domain of approximation to the set of stable filters. A nonlinear optimization algorithm is employed to perform the minimization.

The second approach to rational filter design is based on a 2-D linear prediction algorithm. The prediction algorithm is used to obtain an all-pole approximation to a desired spectral function. The approximation is an infinite Levinson expansion in terms of reflection coefficient functions. The expansion is truncated, retaining only the most significant RCF's, in order to obtain a realizable filter. With modifications, the method is shown to be useful for all-pass filter design. A method for transforming the phase approximation problem to a spectral factorization problem is presented, in which the prediction algorithm is employed to perform the factorization. The spectral factor is used to construct the appropriate all-pass transfer function.

In addition to simplifying stability constraints, the RCF characterization leads to an efficient lattice structure realization for 2-D recursive filters. Two lattice configurations are examined in detail.

A number of design examples are presented, illustrating the effectiveness of both techniques. The examples are filters useful in the exploration seismology problem. Special attention is paid to the design of fan filters for wave equation migration processing.

5. SIGNAL RECONSTRUCTION FROM PHASE OR MAGNITUDE

U.S. Air Force (Contract F19628-80-C-0002)

Monson H. Hayes, Jae S. Lim, Alan V. Oppenheim

For both continuous-time and discrete-time signals, the magnitude and phase of the Fourier transform are, in general, independent functions, i.e., the signal cannot be recovered from knowledge of either alone. Under certain conditions,

however, relationships exist between these components. For example, when the signal is a minimum phase or maximum phase signal both the log magnitude and phase can be obtained from the other through the Hilbert transform. This relationship has been exploited in a variety of ways in many fields including network theory, communications, and signal processing. As a result of some research into the general problem of signal reconstruction from phase or magnitude, several sets of conditions have been specified for which a discrete-time sequence is uniquely specified, to within a scale factor, by the phase of its Fourier transform, without the restriction of minimum or maximum phase. The first set of conditions considers the case in which the phase is specified at all frequencies whereas the second set considers the case in which the phase is specified only at a discrete set of frequencies. Once these conditions have been established, a dual set of conditions are presented for which a discrete-time sequence is uniquely specified to within a sign and a delay by the magnitude of its Fourier transform, again without the restriction of minimum or maximum phase.

For those sequences satisfying the appropriate set of conditions, three algorithms have been devised for reconstructing a sequence from its phase or samples of its phase. The first algorithm is conceptual in that it provides some insight into the fundamental results of phase or magnitude signal reconstruction. The remaining two algorithms are numerical and provide a practical method of performing phase-only signal reconstruction. The first numerical algorithm is an iterative technique in which the estimate of the desired sequence is improved at each iteration. The second is a closed-form solution for which the desired sequence is found by solving a set of linear equations.

Although stated only in terms of one-dimensional sequences, the results are readily extendible to multidimensional sequences. This extension is accomplished by utilizing a few well-known results on projection and slices. With this extension, a potential application for phase-only reconstruction is the blind deconvolution of images which have been blurred by a symmetric point-spread function.

Further research is expected to address such questions as the noise sensitivity of reconstruction techniques, the convergence properties of iterative solutions, the existence of more efficient algorithms that may be realistically applied to processing large amounts of data, alternate forms of the multidimensional theorems which do not depend on projection/slice ideas, and the extension

of the known results to include additional constraints on the sequence (such as positivity).

6. TIME-SCALE MODIFICATION OF SPEECH

U.S. Navy — Office of Naval Research (Contract N00014-75-C-0951)

Samuel Holtzman, Michael R. Portnoff, Jae S. Lim

We have implemented an analysis-synthesis system on our PDP-11 computer that performs uniform-rate speed transformations on speech signals. The problem of spectral degradation and introduction of noise, which usually occur in similar systems, are not found in this one. This is because the system performs the transformations in the frequency domain by means of the discrete short-time Fourier transform rather than in the time domain.

In order to achieve an even more natural-sounding result, we are at present introducing nonuniformities into the speed transformations to incorporate a dependency of the system on local features of the speech signal being transformed.

Our work has been directed toward the development of an algorithm to automatically segment the speech signal into a sequence of passages for which an expected level of degradation, caused by uniform time-scaling, can be determined. The purpose of segmenting the signal in this manner is to allow the degree of local time-scale modification to be decreased whenever the expected level of degradation is high.

The algorithm uses a statistical analysis of the speech signal to determine a level of local quasi-stationarity which, based on our model of speech production, is highly correlated with the expected level of local degradation.

7. THE ESTIMATION OF FORMATION PARAMETERS IN SONIC WELL LOGGING

U.S. Navy — Office of Naval Research (Contract N00014-75-C-0951)
Schlumberger-Doll Research Center Fellowship

Andrew L. Kurkjian, Alan V. Oppenheim

The sonic well logging problem is modeled as an ideal point source in an infinite fluid cylinder surrounded by an elastic solid. There is an ideal point

source on the borehole axis whose waveform is assumed to be known. The borehole radius and parameters of the fluid are also assumed to be known. An ideal array of point receivers is placed along the borehole axis a known distance from the source. The problem is to estimate the parameters of the solid formation from the received signals.

Existing estimation schemes are based on overly-simplified physical models of the acoustical field. Consequently, these methods have achieved only limited success. The purpose of this research is to develop a signal processing procedure which takes into account more of the fundamental physical behavior of the problem than existing methods. This interdisciplinary approach to the problem is expected to lead to superior estimation techniques.

8. SPECTRAL ESTIMATION FOR SENSOR ARRAYS

National Science Foundation (Grant ENG76-24117)
Hertz Foundation Fellowship

Stephen W. Lang, James H. McClellan

The processing of signals from sensor arrays has applications to areas such as radar, sonar, seismology, and radio astronomy. In several important cases, far-field imaging, for example, the type of processing desired can be classified as power spectral estimation. Current areas of research interest are the investigation of techniques for estimating power spectra and the interaction between the selection of a spectral estimation algorithm and the design of arrays.

There is no one best way to estimate spectra; the circumstances and requirements of a particular application may favor one estimation technique while putting another at a disadvantage. For example, the data or input requirements of a spectral estimation technique can affect its utility. Does it require time series data from each sensor or does it begin with correlation measurements between sensors? Does it require regularly sampled data or can it handle irregular sampling? Computational considerations are also important. Does an algorithm exist to compute the spectral estimate with a reasonable amount of effort? Performance is an issue. How well does the estimation technique perform with the spectra likely to be encountered?

In recent years many new spectral estimation techniques have been introduced. However, many of them have only been developed in the context of one-dimensional spectral estimates using evenly sampled data. It would be of great interest to use ideas which led to these one-dimensional techniques in developing spectral estimation techniques and computational algorithms more suitable for use with sensor arrays: multidimensional estimates from irregularly spaced sensors.

Array design is intimately related to spectral estimation; the design of the array determines what information is available to be processed. The relationship between array design and the performance spectral estimation is therefore of interest.

9. SPEECH ENHANCEMENT

U.S. Navy – Office of Naval Research (Contract N00014-75-C-0951)

Jae S. Lim, Alan V. Oppenheim

Degraded speech occurs in a variety of contexts, and its enhancement is desirable for many practical applications. In our past research on this problem, we have developed several systems for enhancement and bandwidth compression of noisy speech by attempting to estimate the parameters of a specific underlying speech model based on the Maximum A Posteriori (MAP) estimation procedure. When the systems were implemented and applied to real speech data, they performed well as enhancement and potential bandwidth compression systems of noisy speech at various S/N ratios. As a practical application area, we have applied our speech enhancement systems with successful results in reducing quantization noise in PCM speech coding. Our future research in this area will include investigation of methods to improve our current speech enhancement systems, development of new systems, and application of speech enhancement systems to practical problems.

10. TWO-DIMENSIONAL POWER SPECTRUM ESTIMATION

U.S. Air Force (Contract F19628-80-C-0002)
Government of Pakistan Scholarship

Naveed A. Malik, Jae S. Lim

Power spectral density estimation occupies a place of fundamental importance in such diverse fields as speech processing, seismic signal processing, image restoration, radar, sonar, radio astronomy, etc. The current research is directed toward the characterization and understanding of existing two-dimensional power spectrum estimation (PSE) methods, and the development of high-resolution techniques applicable to two-dimensional and higher signals.

Most of the conventional PSE methods extend in a straightforward manner from one to two dimensions. However, important high-resolution techniques, such as the Maximum Entropy Method (MEM), pose highly nonlinear problems when applied to two-dimensional signals. The MEM solution has been shown to have an autoregressive or all-pole form for problems of any dimensionality. Further, an important new result by Woods proves the existence and uniqueness of the MEM solution to the two-dimensional PSE problem under certain constraints.

In order to gain an understanding of the problem, the performance evaluation of various ad hoc autoregressive (all-pole) spectral estimators has been performed. These models were derived via a minimum mean-square-error algorithm, using a linear prediction type of problem formulation.

The shape of the autoregressive (AR) filter mask is arbitrary in two dimensions, and for the purposes of PSE, even causality of the filters is not an issue. Thus the AR problem formulation is not unique in two dimensions. Various filter

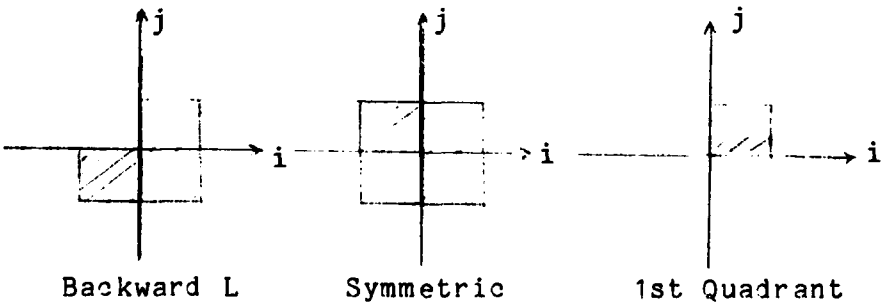

Fig. XXII-1. Filter mask shapes.

mask shapes have been investigated, including the 'L'-shaped filter, the symmetric filter, and single-quadrant filters (Fig. XXII-1).

It was found that the spectral estimate was 'stretched' or distorted from the true shape, the distortion being a function of the mask shape employed. Further, the mask shape also dictates the resolution properties of the filters, which can be very directional in nature. It has been conjectured that the stretching is due to the nonsymmetric shape of the region over which information about the signal is available (i.e., a nonsymmetric autocorrelation function region). As such, complementary filter sets (such as the 'backward L' and 'forward L' shapes) can be found such that the average of their spectral estimates provides a reasonably good, undistorted estimate of the power spectrum of the signal. The AR filters certainly perform better than the conventional periodogram-type estimators, and given some a priori information about the signal generating process, it may be possible to make an intelligent choice of the filter mask to obtain a good power spectrum estimate.

The current area of interest is the true MEM problem, and an iterative method of obtaining the MEM solution is being investigated. Tests of the algorithm in the one-dimensional case (where the exact MEM solution is available for comparison) have been completed, and now the extension to two dimensions is being performed. The technique seems to hold a lot of promise in cases where the signal-to-noise ratio is very low. The method is completely general, and if results indicate its viability as a PSE technique, the extension to problems of any dimensionality should be fairly straightforward.

11. EXTRACTION OF ACOUSTIC PLANE-WAVE REFLECTION COEFFICIENT FROM THE SOUND FIELD GENERATED BY A POINT SOURCE

U.S. Navy – Office of Naval Research (Contract N00014-77-C-0196)

Douglas R. Mook, Alan V. Oppenheim, George V. Frisk
[G.V. Frisk is with the Woods Hole Oceanographic Institution.]

Under the assumption of horizontal stratification, the ocean floor can be characterized by an acoustic plane wave reflection coefficient which is a function of angle. When measurements are made using a point source, this function

can be extracted from the reflected pressure field by using the Hankel transform. The merits of this approach for practical problems were examined during the past year. Future work will concentrate on using theoretical results to derive a model based scheme for extracting the reflection coefficient.

12. MAXIMUM LIKELIHOOD ESTIMATION WITH NOISY DATA

U.S. Navy – Office of Naval Research (Contract N00014-75-C-0951)

Bruce R. Musicus, Jae S. Lim

Maximum Likelihood (ML) Estimation is a powerful tool for estimating model parameters or signals from observed system output. Not only does it yield estimates with nice theoretical properties, but the estimates are also easily calculated for many useful signal models. Unfortunately, when both the parameters of the system as well as the system output must be estimated from observations corrupted by noise, Maximum Likelihood Estimation usually requires a difficult nonlinear optimization. Three different ML approaches have been proposed for estimating the signal and parameters of a system from noisy observations. We have found iterative algorithms for solving each of the three problems, which effectively decouple the uncertainty in the parameter and signal values, thus simplifying the calculation required. When applied to a particular pole-zero model, all three algorithms iterate back and forth between linearly filtering the observations to estimate the signal and fitting parameters to the signal estimate by solving linear equations. The theoretical properties of the algorithms, their relationship to methods previously proposed by Lim, and their application to a variety of signal models have been studied. Present work on these algorithms is focusing on testing their performance with real data, and on developing adaptive real-time versions of the algorithms.

13. PROCESSING OF SATELLITE IMAGERY

U.S. Air Force (Contract F19628-80-C-0002)

Syed H. Nawab, Alan V. Oppenheim, Jae S. Lim

Investigations are being carried out to develop and apply signal processing techniques for problems associated with the processing of multispectral satellite imagery (e.g., LANDSAT). In particular, the problems of restoration and registration are being addressed. Because of the multispectral as well as multitemporal availability of the image data, the signal processing aspect is challenging and has substantial potential for innovation.

14. EVALUATION OF CIRCULARLY SYMMETRIC TWO-DIMENSIONAL FOURIER TRANSFORMS AND ITS APPLICATION TO THE MEASUREMENT OF OCEAN-BOTTOM REFLECTION COEFFICIENTS

U.S. Navy — Office of Naval Research (Contracts N00014-75-C-0951 and N00014-77-C-0196)

Alan V. Oppenheim, George V. Frisk, David R. Martinez

[G.V. Frisk is with the Woods Hole Oceanographic Institution.]

[D.R. Martinez was with the M.I.T.-W.H.O.I. Joint Program in Oceanography/Oceanographic Engineering; he is currently with ARCO Oil and Gas Company, Dallas, Texas.]

In a variety of applications the need arises for the evaluation of the two-dimensional Fourier transform of circularly symmetric functions. Because of the circular symmetry, the two-dimensional Fourier transform reduces to the Fourier-Bessel or Hankel transform. This research considers a method for evaluating this transform using the "projection-slice" theorem for multidimensional transforms. The method is applied specifically to the measurement of the plane-wave reflection coefficient of a horizontally stratified ocean bottom using the fact that, for a point source, the bottom-reflected field and the plane-wave reflection coefficient are circularly symmetric and are related through a two-dimensional Fourier transform.

15. SHORT-TIME FOURIER ANALYSIS

Michael R. Portnoff

Short-time Fourier analysis is based on the notion of a multidimensional representation for a one-dimensional signal. Specifically, a one-dimensional time signal, $x(t)$, is represented by a two-dimensional function of time and frequency, $X(t,\omega)$, called a short-time Fourier transform (STFT). In its simplest form, the STFT $X(t,\omega)$ is defined as

$$X(t,\omega) = \int_{-\infty}^{\infty} x(\tau)\, w(t - \tau)\, e^{-j\omega\tau}\, d\tau,$$

where $w(t)$ is a window function that is, in some sense, narrow in time or frequency, or both. In its more general form, the STFT is defined using a window that is allowed to depend on both time and frequency.

Short-time Fourier analysis is particularly useful for studying "slowly time-varying" phenomena such as speech, music, and other acoustic signals, because rapidly varying local features appear as functions of frequency in the STFT, whereas slowly varying global features appear as functions of time. Thus, the STFT is a formal mathematical description for our notion of a "time-varying spectrum." Furthermore, short-time Fourier analysis is, in many ways, analogous to the acoustic processing performed by the human auditory system.

Our research in this area has been completed with a better understanding of this method of signal analysis, and we are in the process of reporting our research results in the literature.

16. PHASE ESTIMATION

U.S. Navy — Office of Naval Research (Contract N00014-75-C-0951)

Thomas F. Quatieri, Jr., Alan V. Oppenheim

The phase estimation problem for discrete-time sequences was first encountered in the development of a mixed-phase homomorphic vocoder, where the smooth-phase estimate of the vocal-tract impulse response led to harsh-sounding synthetic

speech. The sensitivity of the unwrapped-phase envelope to time-domain perturbations was observed to be greater than that of the log-magnitude spectrum. These observations initiated a number of questions and answers about properties, relations, and estimation procedures of the magnitude and phase of a Fourier transform.

In particular, a theoretical framework was developed for unwrapped-phase estimation from harmonic spectra (voiced speech) through smoothing real and imaginary spectral components. Short-time homomorphic analysis and a short-time harmonic model have led to pitch-adaptive duration and alignment requirements on time-domain windowing. The underlying phase envelope is consequently preserved so that cepstral windowing can be applied. The result is a mixed-phase homomorphic vocoder of somewhat higher quality than its minimum-phase counterpart.

In addition, two alternative mixed-phase vocoders were considered: the first is based on linear interpolation of complex harmonic peaks, and the second on Lim's homomorphic spectral-root deconvolution scheme.

Also, iterative procedures have been developed for recovering the magnitude from the phase function, and, likewise, the phase from the magnitude function. These algorithms are applicable to phase and magnitude estimation, and are easily extended to two dimensions. The reconstruction of phase or magnitude from the known component relies on constraints such as finite duration and causality. In some cases, convergence of the algorithm to a unique phase or magnitude can be demonstrated.

We are currently considering the application of these iterative techniques to the restoration of degraded images with emphasis on phase estimation when a magnitude estimate is known.

Finally, a new method of phase estimation has been developed which transforms the phase estimation problem to a magnitude estimation problem. The advantage of this procedure is that established magnitude estimation techniques (e.g., Wiener filtering) can be applied to phase estimation.

XXIII. SPEECH COMMUNICATION

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(XXIII. SPEECH COMMUNICATION)

1. STUDIES OF SPEECH PRODUCTION AND PERCEPTION

National Institutes of Health (Grant 2 R01 NS04332 and
Training Grant 5 T32 NS07040)
C.J. LeBel Fellowships

Sheila E. Blumstein, Rodolfo Concia, Bertrand Delgutte, Jorge A. Gurlekian, Morris Halle, William L. Henke, David Isenberg, Samuel J. Keyser, Patricia A. Keating, Dennis H. Klatt, Ralph N. Ohde, Joseph S. Perkell, Stephanie Seneff, Christine H. Shadle, Stefanie Shattuck-Hufnagel, Kenneth N. Stevens, John R. Westbury, Victor W. Zue

a. Segmental Aspects of Speech

As part of our continuing series of studies on the perceptual, acoustic, and physiological bases for the phonetic features, we have been examining cross-linguistically the acoustic and articulatory attributes of stop and fricative consonants with different places of articulation, particularly those produced by raising the tongue blade — the so-called coronal consonants. These studies during the past year have included: an investigation of the acoustic and articulatory correlates of the opposition between /s/ and /š/ in English, and similar oppositions for fricatives in several other languages; a study of the acoustic differences that account for the contrast between dental and alveolar consonants that occurs in some languages; observations of the distinctive acoustic attributes for retroflex consonants; a perceptual study of certain acoustic cues for the identification of the Argentine Spanish fricatives /s/ and /f/; a detailed acoustic study of the characteristics of the frication burst, the aspiration noise, and the onset of voicing for voiceless stop consonants in English; and development of a mechano-acoustic model of the aerodynamic events immediately following release of stop consonants, in order to explain in detail the nature of the acoustic events at the release for different places of articulation.

b. Peripheral Constraints on Speech Timing for Vowels

In this study we have examined the temporal and amplitude characteristics of electromyographic activity in the jaw-lowering musculature relative to the durations of vowels whose articulations differ in displacement of that structure. The

principal concern of this work – involving recording of vertical movements of the mandible via a strain gauge, and electromyographic recordings from the anterior belly of digastric via intramuscular hooked wires – is to discover the interrelationships between strength and duration of muscle activity, duration and magnitude of articulatory displacement, and the acoustic duration of speech segments. It is anticipated that this research will provide insight into principles which govern the control of time in the speech signal.

c. Motor Control During Speech: Implications from a Study of Respiration

In collaboration with Dr. P. Schonle (University Hospital, Tübingen), we have conducted an investigation of the temporal and amplitude characteristics of electromyographic activity of certain of the respiratory muscles relative to abrupt speaker-generated variations in upper airway resistance. The focus of this work is to determine whether the inspiratory and/or expiratory muscles exhibit either anticipatory or short-latency (compensatory) activity relative to aerodynamic loadings and unloadings which accompany the articulation of individual speech sounds.

d. A Reaction Time Study of the Production of /s/ and /š/

This study is designed to reveal dynamics of preparation and movement in the articulation of fricative consonants following vowels. Measures were obtained of the time to initiate and to complete articulation of /s/ and /š/ following a go-signal during a steady vowel. Systematic differences in reaction time were obtained for different fricatives and vowels, and these differences appear to be linked to "activation time of the motor programs" for the two fricatives rather than to movement difficulty per se.

e. Phonological Structure of the Mental Lexicon

Previously published data on spontaneous speech errors have been examined in order to speculate on the representational form of words in the mental lexicon that is accessed during speech production. The analysis suggests that words are represented in terms of morphemes, which are, in turn, represented in terms of phonemes.

There is little evidence in the error corpus for independently moveable distinctive features or syllables as phonologically real processing units, although the concept of a syllable does play a useful role in specifying positional constraints on phonetic movement in an error. Words appear to be processed as if they were composed of linear sequences of phonemes.

f. Toward a Measure of Phonetic Similarity

As part of our effort to develop a new model of speech perception and lexical access, we are developing a metric for comparing an input spectrum with a spectral template, independently of the nature of the speech spectra to be compared. A set of 66 vowels acoustically similar to /æ/ were synthesized by adding together sinusoidal harmonics, and these vowels were presented to subjects in separate tests of psychophysical distance and phonetic distance. This work is continuing with additional types of stimuli, and preliminary results suggest that a metric can be developed without explicitly computing formant-frequency values.

g. Intrinsic Pitch of Vowels in Sentence Context

As a first step toward an understanding of how the intrinsic fundamental frequency (F_0) of vowels interacts with intonation in running speech, the fundamental frequency of the vowels /i,a,u/ was examined in a controlled sentence context. Results were obtained for four speakers at four locations in sentences matched for length and stress pattern. Vowel height was observed to influence fundamental frequency at all locations in the sentence except sentence-final position. Various hypotheses have been proposed and additional acoustic measurements have been made in order to explain these results in terms of acoustic and/or physiological interactions between supralaryngeal and laryngeal activity.

h. Study of the Phonological Processes in American English

We are continuing our research that seeks to obtain quantitative information on the variation of the properties of speech sounds in context. As a part of this program, we have been examining various palatalization effects that occur across

word boundaries, including the palatalization of word-final /s/ or /z/ followed by /y/. These and other sentence-level effects are being measured from a large corpus of data, and are being organized into a set of rules that describe the effects in a systematic way. One source of new insights into these rules is our continuing project on spectrogram reading, in which members of our research group are improving the speed and accuracy with which they can interpret phonetic information in spectrograms.

i. Representation of Speechlike Sounds in the Discharge Patterns of Auditory Nerve Fibers

We are collaborating in this work with the Eaton-Peabody Laboratory of Auditory Physiology, Boston, Mass. In order to study how acoustic characteristics important for speech discrimination can be coded at the level of the auditory nerve, responses of auditory-nerve fibers to speechlike stimuli were recorded in anesthetized cats. Results demonstrate that a knowledge of response properties for simple stimuli is useful to interpret responses to speechlike sounds.

Response patterns of single fibers show a peak in discharge rate just after the onset of a stimulus with a rapid onset. This peak is more prominent for a /č/-like noise burst (with an abrupt onset) than for a /š/-like burst (with a gradual onset). Following the offset of a stimulus to which a unit responds, there is a recovery period during which the unit responds at a lower discharge rate to test stimuli. This effect (analogous to forward masking) was demonstrated for a synthetic /ma/ stimulus: During the formant transitions following the low-frequency nasal murmur, fibers with low characteristic frequencies (i.e., those that responded to /m/) discharged at a lower rate than they did for a /ba/ stimulus with identical formant transitions. The coding of fundamental frequency was investigated using single-formant synthetic stimuli. At sound levels typical of speech, information about fundamental frequency is present as periodic fluctuations in the short-time average discharge rate of units over a wide range of characteristic frequencies (CF). Experiments with /s/ and /š/-like noise bursts suggest that there is information in the profile of average discharge rate vs CF that could be used to distinguish between the spectra of these sounds. The results of pilot

experiments on responses to speechlike sounds presented in a continuous noise background suggest that the noise can affect more or less strongly the manner in which particular acoustic characteristics of speechlike sounds are represented.

j. A Speech Analysis-Synthesis System with Separable Models for Spectrum Envelope and Excitation

A speech analysis-synthesis system has been developed which separates the speech waveform into a model for the vocal-tract transfer function and an excitation model. Both components can then be modified independently, and speech can be reconstructed with a transformed spectrum and/or transformed pitch. The system does not make use of a simple excitation model that would require the extraction of a sequence of pulses spaced by the fundamental period, and therefore the reconstructed speech is more natural-sounding than typical vocoder speech. The system has potential applications in a number of different areas, such as speaker normalization for computer speech recognition, studies of female versus male voice quality differences, modification of speech rate, spectral modification of speech (as a potential aid to persons with residual low-frequency hearing), and implementation of a baseband-excited vocoder, in which the upper portions of the reconstructed excitation spectrum are generated from the lower portion.

k. Software for a Laboratory Speech Synthesizer

The software formant synthesizer that has been used in our laboratory for a number of years to generate stimuli for perceptual experiments has been fully documented and published as a set of Fortran programs. The theory of formant synthesis is presented and strategies for the imitation of a number of English speech sounds are presented in tabular form.

l. Refinement of Videofluorographic Techniques for Studying Articulation

As a continuation of work on reducing radiographic dosages for x-ray studies of speech production, an experiment was run to improve the resolution of pellet-tracking measurements using frame-by-frame analysis of videotaped fluoroscopy. A paraffin wedge was used to produce more uniform exposure density and a relatively

large lead pellet was affixed to the tongue. Accuracy of resulting plots of pellet movement was found to approach the accuracy obtained from cineradiographs with a dosage reduction of a factor of 40 as compared to conventional 35-mm cineradiography.

m. A Magnetic-Field Ranging Device for Studying Midsagittal Plane Movements of Points inside the Vocal Tract

A 3-channel magnetic-field ranging device has been constructed incorporating previously used principles. Two large transmitting coils, each excited by a sinusoidal signal at a different frequency, are mounted on a helmet above the forehead and below the occiput. Extremely small transducer-receivers consist of inductors mounted on a base with lead wires attached. The transducers are attached to the structures of interest and leads are brought out of the corner of the mouth. The magnetically induced signal in each transducer is demodulated to produce voltages which are related to distances between transmitters and transducer, allowing for spatial localization by triangulation. In spite of technical problems which remain to be resolved, the potential usefulness of such a device has been demonstrated in a test on 3 subjects of a hypothesis about the na ure of articulatory targets for point vowels.

n. Speech Synthesis by Rule

The MITalk-79 text-to-speech system that has been under development at M.I.T. for a number of years under the direction of Professor Jonathan Allen has been fully documented as a monograph. The monograph includes chapters by Jonathan Allen describing an overview of the system and its potential future as a practical device; chapters by Sheri Hunnicutt on morphemic decomposition, letter-to-sound conversion, partial syntactic analysis, and fundamental-frequency contour generation; chapters by Dennis H. Klatt on prediction of segmental durations, phonological recoding, phonetic-to-parametric conversion, and the theory of formant synthesis; and a chapter by David B. Pisoni on a detailed evaluation of the intelligibility and comprehensibility of words, sentences and paragraphs produced fully automatically from English text. The MITalk-79 system has been frozen as

a set of BCL programs that can be obtained by license agreement with the M.I.T. Patent Office.

2. STUDIES OF SPEECH PRODUCTION BY CHILDREN AND DISORDERS OF SPEECH PRODUCTION

National Institutes of Health (Grant 2 R01 NS04332 and Training Grant 5 T32 NS07040)

National Science Foundation (Grant BNS77-26871)

C.J. LeBel Fellowship

Suzanne Boyce, Marcia A. Bush, Ursula G. Goldstein, Howard L. Golub, William L. Henke, Lise Menn, Kenneth N. Stevens

a. Modeling the Effects of Growth on Vowel Production

A static articulatory model incorporating growth parameters has been developed to study the effects of anatomy on women's and children's production of vowels. The model is characterized by articulatory variables specifying a number of parameters influencing vocal-tract shape, including the position of a circular tongue body relative to the angle of the jaw. The sizes of parts of the vocal tract are specified by growth curves which express anatomical distances as a function of age. Vocal-tract length and cross sections in the midsagittal plane are computed and used as the basis for determination of area functions and formant frequencies. The model is used to compute formant frequencies when age and sex of the speaker are given, along with positions of the articulators appropriate for particular vowels. The next step in this research is to examine the formant frequencies for vowels produced by the model for children, women, and men, and to compare these model-generated data with data from real speech, in an effort to explain the non-uniform scaling that has been observed in the formant frequencies for different vowels.

b. Diagnostic Use of the Infant Cry

We have attempted to advance our understanding of the diagnostic value of the infant cry by extending past work in two directions. First, we have developed a

model of cry production that will enable the observer to relate more closely the acoustic properties of the cry to the anatomical and physiological characteristics of the infant producing the cry. Second, we have refined the procedures for extracting parameters from the sound, for deriving features from these parameters, and for statistical analysis of the data by making use of the computer-based signal processing and data-manipulation capabilities that have been developed in recent years by speech researchers. Recently, we have completed a pilot study analyzing the cry of about 50 normal infants and about 50 infants with several different abnormalities. Based on the model of cry production and on statistical analysis of the cry data, eight diagnostic tests were designed by combining a number of acoustic features extracted from the cry. The cry for infants with medical abnormalities shows certain characteristics that deviate from those for normal infants, depending on the type of abnormality. These deviant characteristics include acoustic evidence that indicates respiratory problems, instability of laryngeal control, and constricted vocal tract. Although the number of infants in the different abnormal groups is small, there are indications that, with judicious selection of features and diagnostic tests, infants with particular abnormalities can be identified with a reasonable probability of success, and a relatively small false alarm rate.

c. Pitch and Marked Voice Quality in Parent-Child Discourse: Acoustics and Semantics

We have completed the acoustic analysis of recordings from 16 parent-child conversations. The children were aged 2 to 5, and the conversations took place in a semistructured laboratory playroom situation. We are proceeding with an analysis and interpretation of the data. In particular, we are examining the pitch contours during these interactions to determine the extent to which regularities in pitch ranges occur in successive clauses (within and across speakers) as the semantic focus of the discourse is maintained or as it shifts.

d. Control of Fundamental Frequency by Profoundly Deaf Speakers

The general goal of this study is to determine by an acoustic analysis the relationship between segmental articulation and laryngeal control by profoundly

deaf boys and girls. In particular, we are trying to discover whether some of the exaggerated variations in voice fundamental frequency (FO) produced by deaf speakers are a consequence of inappropriate articulatory maneuvers and/or laryngeal postures used in vowel and consonant production. The results of preliminary analyses indicate that an excessively high FO is often associated with the deaf speaker's production of high vowels and of vowels following voiceless consonants. For some deaf boys and girls, these deviations in FO appear to be correlated with the use of "extreme" articulatory strategies (e.g., excessive aspiration, exaggerated formant (tongue/jaw) movement). Implications of these findings for the development of speech-training procedures are also being considered.

e. Acoustic Study of the Effects of Intubation on Laryngeal Function

In collaboration with the Anesthesiology Department at Beth Israel Hospital, we have conducted a study to determine the effects of intubation on laryngeal function. Recordings of vocalizations of patients were made before intubation (preoperative) and postoperatively at various times after intubation. Acoustical analyses of these recordings were performed to seek evidence for changes in the vocal-fold vibration pattern that might be the result of temporary or permanent influences on the vocal folds as a consequence of intubation. In most patients who have been intubated for several hours, there was evidence for changes in the vocal-fold vibration pattern, and for gradual recovery to the preoperative condition within a few days.

XXIV. LINGUISTICS

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National Institute of Mental Health (Grant 5 PO1 MH13390)

Morris Halle

The ultimate objective of our research is to gain a better understanding of man's mental capacities by studying the ways in which these capacities manifest themselves in language. Language is a particularly promising avenue because, on the one hand, it is an intellectual achievement that is accessible to all normal humans and, on the other hand, we have more detailed knowledge about language than about any other human activity involving man's mental capacities.

Scientific descriptions of language have for a very long time followed a standard format. A number of topics are almost invariably discussed; for example,

pronunciation, the inflection of words, word formation, the expression of syntactic relations, word order, and so forth. Moreover, the manner in which these have been treated has also been quite standard. While traditional grammars have many shortcomings, their great practical utility is beyond question; generations of students have acquired adequate command of innumerable languages with the help of grammars of the standard type. A plausible inference that might be drawn from this fact is that languages are somehow not very different from one another and the traditional standard format has succeeded in capturing essential aspects of what all languages share in common. Accordingly, much of the research of our group has been devoted to studying the common framework that underlies different languages, the general principles that are exemplified in the grammar of different languages. Results strongly indicate that this assumption is indeed correct as far as the linguistic evidence is concerned.

The preceding discussion leads quite naturally to the question, "What evidence from outside of linguistics might one adduce in favor of the hypothesis that all languages are constructed in accordance with a single plan, a single framework?" It seems to us that the most striking evidence in favor of the hypothesis is, on the one hand, the rapidity with which children master their mother tongue, and, on the other hand, the fact that even a young child's command of his mother tongue encompasses not only phrases and utterances he has heard but also an unlimited number of phrases and utterances he has not previously encountered. To account for these two sets of facts, we must assume that in learning a language a child makes correct inferences about the structural principles that govern his language on the basis of very limited exposure to the actual sentences and utterances. In other words, we must assume that with regard to matters of language a child is uniquely capable of jumping to the correct conclusions in the overwhelming majority of instances, and it is the task of the student of language to explain how this might be possible.

A possible explanation might run as follows. Assume that the human organism is constructed so that man is capable of discovering only selected facts about language and, moreover, that he is constrained to represent his discoveries in a very specific fashion from which certain fairly far-reaching inferences about the organization of other parts of the language would follow automatically. If this assumption is accepted, the next task is to advance specific proposals concerning the

devices that might be actually at play. The obvious candidate is the theoretical framework of linguistics, for while it is logically conceivable that the structure of language might be quite distinct from that of the organism that is known to possess the ability to speak, it is much more plausible that this is not the case, that the structures that appear to underlie all languages reflect quite directly features of the human mind. To the extent that this hypothesis is correct — and there is considerable empirical evidence in its favor — the study of language is rightly regarded as an effort at mapping the mysteries of the human mind.

Additional detailed information on various projects connected with this research is available through inquiry to the department head, Dr. Samuel J. Keyser, Room 20D-105, Ext. 4141.

1. RESEARCH RESULTS

Roman Jakobson

My research during 1977-1978 was directed toward the analysis of the ultimate constituents of language, the smallest discriminative properties of speech sounds. The chief results of this research are summarized in the book, The Sound Shape of Language;[1] included is a short supplement entitled "An Instance of the Interconnection between the Distinctive Features."

My present research is primarily devoted to the interaction of brain and of language, to the unconscious factor in language, and to the metalinguistic operations in the life and development of language. In 1979 this work was conducted in cooperation with Professor Stephen Rudy (Yale University), Miranda Mengis (MIT), and Kathy Santilli (MIT).

I reported on this research during 1979 at the Universities of Jerusalem, Copenhagen, and Moscow, and at the Georgian Academy of Sciences, Tbilisi. A colloquium on this topic was held at the Ruhr-Universität Bochum on January 24, 1980, and the proceedings will appear in a special publication of that University.[2] I discussed this research on March 13 at the University of Minnesota, on April 23 at an interdepartmental meeting of Yale University, and on May 6 at New York University. A volume[3] of studies closely linked to this research has just appeared.

My research work in 1979 also dealt with the earliest Slavic verbal and musical arts, for which I received a Fellowship from the National Endowment for the Humanities. The results of this research will appear in a forthcoming volume of my Selected Writings.[4] My Selected Writings V (edited by Professor Stephen Rudy with the assistance of Martha Taylor, Mouton, The Hague, 623 p.) appeared in 1979. Still another, further volume is to appear in 1980 (Mouton, The Hague, c. 900 p.).

My current publications, including books, papers, and lectures, are listed in the references.[5-13] Items 7-12 are all translations of my writings.

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XXV. COGNITIVE INFORMATION PROCESSING

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1. NATURAL LANGUAGE PROCESSING

National Science Foundation (Grant SED76-81985)

Jonathan Allen

The text-to-speech system for unrestricted English text has been unified in a current version called MITALK-79. A large effort was made to bring all components of the system up to date, and a one-week course was given in June 1979 to those people outside of M.I.T. who wished to understand or acquire the system. A license arrangement has been made, and several universities and companies are currently utilizing the software, demonstrating that the system can, in fact, be successfully

exported. A set of notes was prepared for the summer course and these are now being edited to form a monograph that will soon be published.

As part of the conclusion of this project, a set of intelligibility and comprehension tests was made. These showed that the generated speech quality is acceptable for a wide range of applications, and that listeners can understand spoken paragraphs as well as the same material visually displayed. It is apparent, however, that synthetic speech generated by rule is still not completely natural, even though it may be highly intelligible. This happens because the synthesis-by-rule algorithms utilize a small number of robust cues to mark the various linguistic structures, whereas in human speech, a much richer variety of cues is redundantly produced. A major task is to understand how all of these correlates are produced together and, particularly, how they trade with one another. Equally important is the determination of how these correlates integrate to form percepts. In the coming year, we plan to focus on research which can reveal the nature of this integration metric, and how the perceptual mechanism dynamically weights the strength of the several cues and constraints. A model for speech recognition based on the determination of strong syllable structures, and subsequent lexical access based on these syllables, is currently under development. This model utilizes a principle of focused search, where selected sets of cues are actively examined based on local context so that passive template matching is avoided. The integrative process of perception is thus seen as a selective focus of attention on contextually relevant cues that have strong constraint strength in the immediate environment.

2. DIGITAL WIREPHOTO SYSTEM

Associated Press (Grant)

Donald E. Troxel, William F. Schreiber, Richard S. Damon,
John N. Ratzel, Jason Sara

Since August 1970, we have been developing a news picture (Wirephoto) distribution system that is entirely new for the Associated Press. It is being introduced in stages, in such a way that at least the present standard of quality and service will be maintained everywhere, with improvements spreading gradually to all

locations.

Pictures are stored under computer control. An editor can view any picture on a TV display in order to select, discard, edit, transmit, or store that image for later automatic dispatch. Editing may include cropping, enlarging, reducing, tone-scale enhancement, sharpening, combining, and addition of captions. No additional chemical photographic work will be required for any of these picture-processing operations.

Transmission over the "backbone" system linking AP bureaus and large metropolitan newspapers that have substantial computer facilities will be via high-speed digital links and will originate and terminate generally at computer-controlled digital storage devices. Transmission to subscribers will be analog or digital and at speeds and scanning standards appropriate to the existing transmission facilities. Complete control will be exercised by the New York network monitor. In the absence of manual interventions, transmission to all points among the bureaus, from point to point, and to regional networks, will be accomplished automatically.

We have implemented some of these procedures in the laboratory, using a PDP-11 computer (300-megabyte disk). The input may be a picture from the AP network, from a local analog transmitter, or from magnetic tape, and is stored on a disk. Pictures may be transmitted from the disk to comparable receiving points. Pictures stored on the disk may be viewed on a TV display utilizing a full-frame storage system. Editing facilities already in operation include cropping, enlarging or reducing, combining several pictures into one, addition of captions, and sharpening.

The multitask software operating system permits new picture-processing routines to be integrated easily, and we plan to keep incorporating additional picture-processing routines into the system.

We are particularly interested in picture-processing operations in which the processing depends on the local content of the picture. That is, the detailed parameters of a coding or enhancement scheme vary for different local areas. In this type of processing it is of prime importance to avoid artifacts such as contours outlining these local areas. We are also accelerating our interest in color picture processing, both from the viewpoint of coding for bandwidth compression and enhancement or manipulation.

The Associated Press has now installed the computer-based image processing system in New York City. It is initially being used to coordinate the newsphoto transmissions between the domestic and international Wirephoto networks.

3. DATA PROCESSING FOR THE GRAPHIC ARTS

Providence Gravure, Inc. (Grant)

William F. Schreiber, Donald E. Troxel, Leonard Picard,
Malik M.A. Khan, Sudhindra N. Mishra, Hapet A. Berberian

The aim of this project is to explore the feasibility of digital processing and computer manipulation of graphic arts quality images which are intended to be duplicated on printing presses. Specific areas of investigation include data compression, tone-scale reproduction, enhancement, input/output hardware and software, and the economical storage and retrieval of very large amounts of pictorial data.

4. IMAGE PROCESSING FOR THE GRAPHIC ARTS

Taylor Publishing Company (Grant)

Donald E. Troxel, William F. Schreiber, Phuong-Quan Hoang, John N. Ratzel

Taylor Publishing Company is developing a computer-based system for producing printing plates for yearbooks and similar publications. This type of printing is characterized by a very large number of different pages, most containing many pictures, and by small runs compared with most other publishing. Thus the cost of plate preparation is a high proportion of the total production cost. The purpose of the MIT project is the development of an improved system for the input and processing of the graphical elements — pictures and other nontypographical matter — to be included in the final pages. The improved system is to feature lower cost, higher speed, and no loss of quality through the application of interactive computer techniques.

The work to be done at MIT consists of the design of a scanner station and its operating system. Physically, the station, which itself will be a satellite of the Taylor Publishing Company's publishing system, comprises a small computer with

associated peripherals. These include a picture display, full-frame memory, disk memory, tablet and Autokon scanner. The operating system will permit the station operator, sitting in front of the computer console, to perform, interactively, the following operations:

1. Receive layout instructions for each page, from the central system, including location and size of graphical elements.

2. Scan pictures into the system using parameters derived from the layout information.

3. View scanned pictures on the display and perform aesthetic corrections, if required. View entire page on display to verify layout.

4. Organize graphical data in local memory as required by page layout and initiate data transfer to the central system.

The novel features of this system revolve around the use of a small computer, in combination with a graphics arts quality laser scanner and some special-purpose digital hardware, to permit input of graphic elements, aesthetic corrections, and the organization of data for each page according to layout information, all on an interactive basis, and in a cost-effective manner.

XXVI. CUSTOM INTEGRATED CIRCUITS

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1. CONVERSION OF ALGORITHMS TO CUSTOM INTEGRATED CIRCUITS

U.S. Air Force – Office of Scientific Research (Grant AFOSR-78-3593)

Jonathan Allen, Lance A. Glasser, Paul Penfield, Jr., Ronald L. Rivest, Gerald J. Sussman, Howard Shrobe, John T. Holloway

In this project, the objective is to determine a set of computational transformations which can convert an initial algorithmic specification to a final mask specification suitable for implementation of NMOS circuits. Techniques for manipulating architectures stated in hardware design languages along space/time tradeoffs have been developed, and we are currently creating a language for expressing algorithmic constraints so that the performance of an algorithm can be separated from its competence. This form of algorithmic specification makes performance choices clear, and permits the exploration of architectural alternatives.

A variety of artwork analysis and synthesis programs have been written. These include a layout language, a PLA generator, a design rule checker, a logic simulator, and a router, as well as theoretical results for the optimal placement and routing of interconnect among rectangular modules. Using a high-performance LISP machine with a color monitor, a system for interactive editing of cells has been constructed, which automatically retains constraints due to design rules. These facilities have been used to design a number of interesting chips, including a basic LISP interpreter and an encryption coder.

XXVII. COMMUNICATIONS BIOPHYSICS

A. Signal Transmission in the Auditory System

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1. BASIC AND CLINICAL STUDIES OF THE AUDITORY SYSTEM

National Institutes of Health (Grants 5 P01 NS13126 and 5 K04 NS00113, and Training Grant 5 T32 NS07047)

Nelson Y.S. Kiang, William T. Peake, Thomas F. Weiss

In conjunction with the Eaton-Peabody Laboratory at the Massachusetts Eye and Ear Infirmary we have reported studies concerned with stages of the auditory system from the inner ear to the brain stem.

Inner ear studies, which extend our knowledge of mechanical-to-neural transduction, have primarily involved experiments with alligator lizard. Measurements of basilar membrane motion indicate that tonotopic organization is not present and that the frequency dependence of the basilar membrane motion is similar to that of the stapes motion.[9] Intracellular potentials recorded from the receptor organ of the inner ear in response to clicks can be classified in two categories which probably correspond to receptor cells and supporting cells.[1] Receptor cell responses have large oscillations, which reflect the frequency selectivity of the receptor potential, superimposed on slower depolarizing potentials, which reflect nonlinearities in the mechano-electric transduction process. Supporting cell responses have a component that is sensitive to the click rate and is apparently neural in origin. Responses of cochlear-nerve fibers from the apical end of the receptor organ have

been measured in response to single- and two-tone stimuli. Results[5] show that a close relation exists between measures of frequency selectivity and two-tone rate suppression, suggesting that both arise from a common mechanism.

Recent clinical interest in the use of "cochlear implants" to provide electric stimulation to the inner ear for patients with profound deafness has led to consideration of the problems and desirable properties for such prostheses.[8] Knowledge of auditory-nerve fiber response properties with speechlike stimuli,[2] as well as basic information on the processing of speech by the system,[7] may provide guidance for such efforts. Studies with patients having multiple electrode implants (carried out at the University of Utah) indicate that even crude use of our knowledge of stimulus coding in the auditory nerve makes substantial improvements in the ability of the patients to discriminate certain speechlike stimuli, although this does not imply the ability to understand ordinary speech.[3]

The "feedback" nerve bundles that lead from the brain stem out to the inner ear have been studied in two ways. Physiological experiments have demonstrated that electric stimulation of a part of this system produces reductions in auditory nerve fiber responses which are somewhat dependent on the fibers' response properties and spontaneous firing rate.[4] An anatomical study, in which components of this efferent system were labelled with radioactive methionine, has led to a description of two components of the system which arise in distinct brainstem locations and project to distinct cochlear locations.[10]

Responses of the brain stem recorded from the surface of the skull have been studied by several groups for diagnostic use. A comparison of responses to monaural and binaural stimulation for both cat and human has indicated some similarities[6] and some differences between the responses from the two species.

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XXVII. COMMUNICATIONS BIOPHYSICS

B. Auditory Psychophysics and Aids for the Deaf

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1. INTENSITY PERCEPTION AND LOUDNESS

National Institutes of Health (Grant 5 R01 NS11153-03 and Fellowship 1 T32 NS07099-01)

National Science Foundation (Grant BNS77-16861)

Louis D. Braida, H. Steven Colburn, Nathaniel I. Durlach, Adrian J.M. Houtsma, Mary S. Florentine, Charlotte M. Reed, Rosalie M. Uchanski

This research is concerned with the development of a unified, quantitative theory of intensity perception and loudness, and involves the construction and integration of models of sensory processes, short-term memory, perceptual context effects, and decision making, as well as extensive psychophysical experimentation. During the past year, work has been conducted in four areas: (i) the relation of intensity resolution to auditory-nerve firing patterns, (ii) the relation of intensity discrimination to masking patterns, (iii) the relation of intensity discrimination to loudness, and (iv) intensity resolution and loudness in listeners

with hearing impairments.

i. We have pursued the investigation of the relation between intensity discrimination and the coding of intensity in auditory-nerve fibers. Predicted performance of reasonable models, e.g., an optimally weighted sum of the numbers of firings on individual fibers, depends critically on assumptions about the following aspects of auditory-nerve activity: the nature of randomness; the importance of the time structure relative to the mean rate of firing (count); the saturation of the rate-intensity function; the distribution of thresholds of fibers with a common characteristic frequency (CF); the distribution of CF's over fibers; the shapes of tuning curves, especially the tails; the dependence of the rate-intensity functions both on the CF relative to the stimulus frequency and on other characteristics of the fiber (e.g., spontaneous rate); and the nonlinear interactions that occur with several stimulus components (as in partial masking experiments). In addition, predictions are sensitive to the way information from different fibers is assumed to be combined centrally. Unfortunately, there exist different sets of assumptions that both correctly predict the psychophysical data and are roughly consistent with available physiological data. In spite of the theoretical latitude, many current models make assumptions that contradict available physiological data. A paper on this material has been prepared for publication.

ii. A new phenomenological model of intensity discrimination has been in its predictions compared to data from the literature. The model is based on excitation patterns derived from masking patterns[1] and is similar to that proposed by Maiwald.[2] It is assumed that (a) the excitation of each of 24 critical bands forms the input to 24 independent excitation-level discriminations — one for each critical band, (b) the individual excitation-level discriminations adhere to Weber's Law, and (c) the outputs of the excitation-level discriminations are combined through an optimum decision rule. On the basis of this model, predictions have been made for intensity discrimination of tones as a function of level and frequency and for several conditions of partial masking (including low-pass, band-pass, high-pass, band-stop, and wide-band). In general, the model fits the data in the literature better than the model proposed by Maiwald in which the discrimination is based on the single critical band with the greatest sensitivity.

iii. Work on the relation between intensity resolution and loudness matching

has continued. Specifically, an attempt was made to test an extension of our theory[3] of intensity perception which predicts that two stimuli are matched in loudness when their intensities divide the respective dynamic ranges proportionally in terms of numbers of JNDs. Comparisons between our empirical results and data in the literature, particularly data on loudness matching, revealed that loudness matches depend systematically on details of the matching paradigm, and that the observed variations are roughly of the same magnitude as the precision required to test the theory rigorously. Details of this research have been submitted for publication.[4]

iv. Studies of impaired listeners[5] have focused on (a) the measurement of intensity resolution as a function of level and frequency and (b) the determination of loudness matching functions (either between ears at a given frequency or between different frequencies in the same ear). The purpose of this study is to provide careful, systematic measurements of intensity resolution in impaired listeners as well as to test our theory relating resolution to loudness matching.[3,4]

Intensity resolution was measured at a number of frequencies in the range 500-4000 Hz over essentially the whole dynamic range using a two-interval, forced-choice, symmetric discrimination paradigm with correct-answer feedback. For subjects with unilateral impairment, measurements were obtained at the same frequency in the normal and impaired ears. For subjects with bilateral losses, measurements were obtained at different frequencies in the same ear (including, when possible, one frequency with normal and one with elevated threshold). The data were processed to obtain estimates of sensitivity per bel δ'. Since δ' varies with level and it is currently unclear how to best equate levels for impaired and normal listeners, the results on δ' obtained for impaired ears were compared to the results for normal ears at equal sound-pressure levels (the SPL-comparison), equal sensation levels (the SL-comparison), and equal loudness (the L-comparison). Loudness matches were obtained using the method of adjustment (alternate binaural or alternate monaural, depending on the subject's loss). The results of these loudness-matching tests were used both to test the above-mentioned theory and to achieve the comparison between normal and impaired δ' at equal loudnesses.

Of the 11 impaired listeners tested thus far, five had unilateral losses (so that the comparison between impaired and normal could be achieved using the same

subject). Four of these subjects had cochlear losses (two low-frequency, one high-frequency, and one flat loss) and one had a retrocochlear loss (mild loss with mild slope caused by surgically confirmed vestibular schwannoma).[6] The results for the cochlear cases generally showed normal resolution for the L-comparison; however, for the SPL- and SL-comparisons, the results varied from worse-than-normal to better-than-normal (with the SPL-comparison generally showing poorer resolution relative to normal than the SL-comparison), depending on the subject and/or shape of the audiogram. These cases also tended to show abnormally rapid growth of loudness. The results for the retrocochlear case showed degraded resolution for all frequencies tested and all methods of comparison (SPL, SL, or L). The growth of loudness for this case showed either exceptionally slow growth over the whole range tested or slow growth at lower levels and then normal growth at higher levels (depending upon the test frequency).

The results obtained by pooling all ears with cochlear impairments (13 ears from 10 subjects) and partitioning this pool according to audiometric configuration (low-frequency, flat, or high-frequency loss), and then comparing these results to the pool of all normal ears (9 ears from 9 subjects), showed the following. For subjects with low-frequency loss, in the SPL-comparison and L-comparison the value of δ' fell within the range of normal values; for the SL-comparison the values of δ' were larger than normal. For subjects with relatively flat losses, in the SPL-comparison δ' was below the normal range; in the SL-comparison and L-comparison δ' fell within the normal range throughout the middle portion of the dynamic range but was below normal values at both extremes of the range. For subjects with high-frequency loss, in the SPL-comparison and L-comparison δ' was below the normal range; in the SL-comparison δ' was generally within or slightly below the normal range. Among the three groups of subjects with cochlear impairments, values of δ' were generally highest for subjects with low-frequency loss, next highest for subjects with flat loss, and lowest for subjects with high-frequency loss (independent of the choice among SPL-comparison, SL-comparison, and L-comparison).

Results on the relation between intensity resolution and loudness matching show reasonable agreement between experiment and theory. In most of the cochlear cases, however, the observed result could be equally well fit by assuming that the

matching functions are simply straight lines (on dB coordinates) which interpolate between the match at threshold and a match at equal SPL's near the discomfort levels. One important exception, however, occurs with the schwannoma patient. In this case, the model predicts the results at 3300 Hz (slow growth of loudness at low levels, normal growth at high levels) very accurately, and the results at 500 and 1000 Hz (slow growth of loudness over the whole range tested) very poorly.

Current work on this project includes further testing of the given subjects, testing of additional subjects, and developing improved analysis procedures. One problem that is important when pooling results and that is receiving special attention concerns the question of how best to normalize the results with respect to differences in test frequency and (more importantly) to variations in the relation of the test frequency to the characteristics of the audiogram. Current work also includes an attempt to organize the results of our work and past work reported in the literature into a coherent overview of intensity resolution in impaired listeners (an area that, at least on the surface, is rather confused). This work includes a review of results on the SISI Test, and an attempt to relate the results obtained with this procedure to procedures, such as ours, that require comparison of pulsed tones.

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2. BINAURAL HEARING

National Institutes of Health (Grant 5 R01 NS10916)

H. Steven Colburn, Nathaniel I. Durlach, Kaigham J. Gabriel, Dennis M. Freeman, David T. Gallagher, Louis V. Giordano, Rudolf G. Hausler, Yoshiko Ito, Esther K. Jaffee, Peter J. Moss, Roy P. Russell, Mark E. Schaefer, Ronald A. Siegel, Carl L. Thompson

Our overall goal is to understand binaural phenomena in normal and impaired listeners and to relate these phenomena to physiological data whenever possible. During the past year, significant progress has been made in several areas, including experimental studies of normal hearing, experimental studies of impaired hearing, theoretical studies, work on facilities, and writing reports on past work.

Experimental studies of subjects with normal hearing were conducted in several projects.

First, in a continuation of work done last year, we used frozen noise waveforms to study binaural detection phenomena by comparing homophasic and antiphasic conditions in terms of the resolution and bias for individual noise waveforms. In the experimental runs, the waveform presented on a given trial was chosen randomly from a set of 10 waveforms. We found that the resolution varied considerably from waveform to waveform in both NOSO and NOSπ conditions. Therefore, the estimates of the ratio of internal to external noise powers calculated with other assumptions from results in two-interval experiments must be revised.

Second, we tested the ability of subjects to discriminate interaural correlation for different bandwidths of the noise signal (Gabriel, 1979; Gabriel and Colburn, 1980). This study is very important to theoretical development since most theories of binaural hearing are (or can be) stated in terms of interaural correlation operations; these data allow direct tests of the basic postulates of the models. One surprising results is that discrimination performance from a reference correlation of unity deteriorates as bandwidth is increased beyond the critical band, even when the noise power per cycle is constant (fixed N_0). In other words, the subjects are apparently unable to restrict attention to a critical band in this experiment; if they could, performance would not deteriorate because the

characteristics of the internally processed signal would not change for supercritical bandwidths. In another correlation study, we measured the abilities of a common set of subjects to discriminate interaural correlation and to detect target bands of noise in analogous cases (Gallagher, 1979; Gabriel, Gallagher, and Colburn, 1980). Models of detection based on correlation discrimination are used to predict the relation between the two sets of results. Although results are in general agreement, a small but consistent discrepancy was found in that detection thresholds were always about one decibel better than predicted.

Third, we conducted several studies focused on the interaction of interaural time and intensity. In a study stimulated by our results from unilaterally impaired listeners, we measured the ability to discriminate interaural time delay in conditions with large interaural intensity differences for wide-band noise and for 500-Hz tones (Russell, 1979). We found, consistent with the results from impaired listeners, that interaural intensity differences have small effects with the noise stimulus but large effects with the tone. We hope that the stimulus dependence of this effect will help us to understand the large effect with tones which has been puzzling us for some time. In an attempt to understand the variability that has been observed in many of our time-intensity studies, we measured the effects of variability in the acoustic coupling of earphones to the ear. Specifically, we compared performance in interaural time discrimination studies with and without the use of an acoustic monitor-and-adjust system applied to the signals in the earphone cavities (Giordano, 1979). Even in the regions with the largest behavioral variability, the monitor-and-adjust system does not appear to be a significant factor compared with the internal variability. Another study (Schaefer, 1979), also motivated by reducing variability, compared training and performance for two paradigms: the standard 2I,2AFC and a 4I,2AFC paradigm recommended by Smith (1976). The four-interval paradigm was easier for the subjects in conditions that are unnatural and confusing; the four-interval paradigm also gave less variability in these conditions. In a study that was motivated by differences between the interaural dependences observed in masking and in discrimination and that was also motivated by the possibility of comparisons with impaired listeners, we measured interaural time-discrimination performance with narrow-band noise signals in a wide-band noise background for several interaural conditions

of the background noise (Ito, Thompson, and Colburn, 1979). We are comparing discrimination with reinforcing interaural conditions in the masker to results with canceling conditions; no significant differences have been observed in our results. These results are also being analyzed in terms of their agreement and disagreement with available models. In a study of image movements for small changes in time delay as a function of reference conditions, we found (Moss, 1979) very complex perceptions and observations that contradicted predictions of our position model (Stern and Colburn, 1978).

Finally, we are studying the process of auditory localization: the acoustic waveforms in the ear canals in response to a click are measured as a function of source position in an anechoic room, and using these results, we attempt to simulate the position of a noise stimulus by generating the expected waveforms in the ear canals using earphones. Even though the waveforms and acoustic signals are being processed very carefully, discrepancies are apparent between performance with real and simulated sources in position-identification experiments (over the surface of a half sphere).

In the experimental studies of impaired hearing, we have also pursued several projects.

We have completed our review of the literature on binaural interaction in impaired listeners (Durlach, Thompson, and Colburn, 1980).

We also conducted experimental studies of subjects with impaired hearing. First, we have completed the study of localization discrimination that was conducted in collaboration with Dr. Rudolf Hausler (Hausler et al., 1979). By measuring discrimination abilities for interaural time and intensity differences and vertical angle as well as horizontal angle at eight reference values around the head, we are able to show consistent patterns of abnormality that correlate with the categories of impairments studied. Among the results of this study are the following: for our subjects with bilateral sensorineural hearing losses, speech-discrimination scores correlated with vertical angle discrimination ability in ways that could not be accounted for by the audiograms; subjects with severe sensorineural losses (75 to 90 dB HL in one subject) were able to discriminate interaural time delay as well or almost as well as many normal listeners when the stimulus was a wide-band noise, although narrow-band performance varied consider-

ably from frequency to frequency and from subject to subject; and performance by subjects with unilateral neurinomas (surgically confirmed vestibular schwannomas with auditory-nerve involvement in every case) was among the worst in each test. We believe that this study will have an important impact on both theories of binaural interaction and our understanding of impaired auditory systems. In the second study, we collaborated on an in-depth study of a single subject with a neurinoma (vestibular schwannoma) involving the auditory nerve on one side (Florentine, Thompson, Colburn, and Durlach, 1979). As part of a large battery of tests, we tested this subject's binaural abilities in interaural time, intensity, and correlation discrimination with a variety of interaural-level differences, including equal SPL, equal SL, equal loudness, and centered. We used both narrow-band and wide-band noises and found no evidence for binaural interaction of any kind (i.e., all abilities could be explained with monaural processing alone). This result is especially significant considering that the subject's audiogram for the affected ear showed a hearing loss of only 20 to 40 dB HL.

Theoretical studies were pursued in several areas. First, theoretical work is included in many of the experimental studies of normal hearing listed above. Second, we are computing the input-output relations of a hypothetical neural network that is designed to process interaural-level differences in a particular frequency region. The computer program has been tested and agrees with analytic computations for special cases that are amenable to analytic treatment. Third, we have begun to develop a theoretical structure for the analysis of binaural interaction abilities in impaired auditory systems (Colburn and Hausler, 1980).

Our work on facilities during the past year has included the design of a two-channel digital-to-analog and analog-to-digital converter system (Jaffe, 1979) that allows output signals to be digitally delayed relative to each other by time delays smaller than the sampling time of the overall system. This converter system when constructed will increase our ability to provide digitally controlled delays with high bandwidth and delay resolution.

Finally, considerable effort has gone into preparing results for publication: four papers were submitted and five more are in draft form and should be submitted within the next two months.

Publications

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3. HEARING AID RESEARCH

National Institutes of Health (Grant 5 R01 NS12846)

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This research continues to be concerned with the development of improved speech-reception aids for persons suffering from hearing loss, and the improvement of fundamental understanding of the limitations on such aids. Our work in this area is focused on the problem of developing improved signal-processing schemes that match speech to residual auditory function for listeners with sensorineural impairments. During the past year, we have continued to study schemes based on linear amplification, amplitude compression, and frequency lowering, and have initiated research on the effects of speaking clearly to improve communication with the hearing-impaired.

Research on linear amplification is primarily concerned with evaluating the extent to which Articulation Theory[1] can be used to predict the dependence of speech intelligibility on frequency-gain characteristic and presentation level for listeners with sensorineural impairments. Initial work,[2] based on the assumption that the impairment could be modelled as an additive noise sufficient to account for the threshold elevation, indicated that the performance of listeners with steeply sloping high-frequency losses using amplification systems with high-frequency emphasis was accurately predicted by the theory. In addition, it appears that good theoretical predictions of the optimum frequency-gain characteristic can be obtained for such listeners. Additional insight into these results has been provided by a recent study[3] which compared the performance of impaired listeners to that for normal listeners with losses simulated by masking noise. According to the results of this study, the masking noise simulated many details of the speech reception performance of listeners with high-frequency losses with good accuracy, but only simulated the average scores for listeners with flat losses. To gain more insight into this problem, we have initiated a study of the intelligibility of speech processed by high-, low-, and bandpass filtering for subjects with a variety of

audiometric configurations induced by sensorineural hearing loss or simulated by masking noise.

Research on amplitude compression for listeners with reduced dynamic range has continued to focus on syllabic compression and has been primarily concerned with analyzing our initial negative results on multiband compression.[4] During the past year effort has concentrated on the development of a new amplitude-compression system and on the study of the role of training in the perception of compressed speech.

i. A new hardware implementation of the 16-band syllabic compression system has been completed.[5] This system continues to be based on 1/3-octave bands, but incorporates log amplifiers in each band to provide greater input dynamic range, finer amplitude resolution, and more precise gain control. Since this system is based on a dedicated microcomputer, it is capable of functioning both as a compressor and as a speech-level analyzer. Systematic measurements of speech-level distributions are being made to permit the characteristics of compression systems to be established accurately and to analyze the properties of compressed speech.

ii. A new study of the intelligibility of amplitude-compressed speech has been conducted.[6] Two impaired listeners were trained for an extensive period to identify a large set of CV syllables processed by multiband syllabic compression and linear amplification. Results for both listeners indicated substantial training effects persisting for roughly 5000 presentations for the listener with a moderate sloping hearing loss, and roughly 20000 trials for the listener with a severe flat loss. Performance after training indicated no advantage for compression for the listener with the moderate loss, and a small but significant improvement for the severely impaired listener. Additional studies of syllabic compression using listeners with severely reduced dynamic ranges are planned.

Research on frequency lowering for listeners with negligible hearing at high frequencies continued to focus on pitch-synchronous time-dilation techniques that can incorporate warping of short-term spectra. A study of the effect of pitch transformation on the intelligibility of synthetic vowels with lowered formants has been conducted using normal listeners with simulated high-frequency hearing losses.[7] Vowels were synthesized with formant frequencies scaled down by a factor of three from values typical of male speech and with fundamental frequencies

either appropriate for the speech or reduced by a factor of two. Results indicate that after training both intelligibility scores and the detailed confusion patterns are unaffected by fundamental frequency reductions up to a factor of two. This suggests that it may be useful to consider including fundamental frequency transformations in future frequency-lowering systems.

Research on the effect of speaking clearly on the intelligibility of speech for impaired listeners has been initiated in order to obtain background information for new methods of matching speech to residual auditory function. In addition, the information gained from this work may contribute to the training of individuals who communicate orally with the hearing-impaired, to the development of procedures for accounting for speaker differences in intelligibility testing, and to basic speech science. Preliminary measurements of the intelligibility of clearly and conversationally spoken sentence material have been made for four listeners with sensorineural hearing loss.[8] Substantial differences in intelligibility scores (18 percentage points) associated with speaking mode were obtained by each listener. Measurements made on the speech waveforms indicated that in clear speech the durations of all speech elements and the number of pauses per sentence increased, and vowels more closely approached target values, but consonant-vowel amplitude ratios increased only for selected consonants. Additional studies currently in progress are concerned with establishing the generality of these results and relating the improvements in intelligibility to changes in the acoustic properties of speech elements associated with the attempt to speak clearly.

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4. TACTILE COMMUNICATION OF SPEECH

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National Institutes of Health (Grant 1 R01 NS14092)
Health Sciences Fund

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The goal of this research is to develop tactile speech communication aids for the deaf and deaf-blind. Our research during the past year can be subdivided into three categories: (a) Study of Tadoma, (b) Development of Artificial Display Systems, and (c) Comparisons of Artificial Systems with Tadoma. A brief summary of work in each category is presented in the following paragraphs.

a. Study of Tadoma

In the Tadoma Method of speech communication, the "listener" receives speech by placing a hand on the talker's face and monitoring actions associated with the speech-production process. We are studying this method in order to document the speech-communication performance achievable with the method and to obtain back-

ground for the design of artificial systems. Work on this method performed during the past year includes (i) an extensive survey of Tadoma use throughout the United States, (ii) in-depth studies of the capabilities of three deaf-blind experienced Tadoma users, (iii) supplementary, less detailed studies of four additional deaf-blind, experienced Tadoma users, and (iv) studies conducted with normal, comparatively untrained subjects in which loss of sight and hearing is simulated by the use of a blindfold and masking noise.

The purpose of the survey is to determine the criteria used for selection of Tadoma trainees, the degree of success achieved with different types of individuals, the types of training programs employed, and the identity of successful Tadoma users. This survey has involved the development of a questionnaire and the submission of this questionnaire to roughly 1000 institutions, as well as numerous interviews with administrators and teachers of the deaf and deaf-blind. The results of this effort are currently being organized and prepared for publication. Roughly 20 blind-deaf successful Tadoma users have been identified by this survey for use in our experimental work.

The experimental research on these deaf-blind experienced Tadoma users[1-4] has been directed toward gaining further understanding of the capabilities of the single Tadoma user studied in our preliminary work and broadening our data base by the inclusion of additional subjects. This research has included study of consonant and vowel confusions in syllable identification tasks, the effect of contextual information and speaking rate on word and sentence reception, the characteristics of the Tadoma users' own speech, and general linguistic competence. In addition, in order to gain further insight into the identity and nature of the perceptual cues employed by the Tadoma user, speech-reception experiments have been performed using restricted hand positions.

Although many of the experiments have produced relatively consistent results across subjects (e.g., tests concerned with the identification of consonants or with the reception of sentences spoken at low rates), some of the experiments have led to results that are strongly subject-dependent (e.g., tests concerned with the use of contextual information, with reception capability at high speaking rates, or with linguistic competence).

In general, it is clear from the results of our experiments with these deaf-blind subjects that it is possible to achieve relatively good speech reception

via the tactile sense and to develop substantial speech-production capabilities and linguistic competence, even when the loss of sight and hearing occurs at a very early age (e.g., under 2 years). Furthermore, these experiments have led to considerable insight concerning the perceptual cues used by subjects to discriminate and identify various speech segments. The principal task now facing us is to determine why the results obtained on these subjects with this method are so superior to past results obtained with artificial devices reported in the literature. Among the factors that are being considered here are (i) the overall richness and multidimensionality of the display, (ii) the direct tie between the display and the speech-production process, and (iii) the very extensive training of the subjects.

The research on relatively untrained normal subjects with simulated blindness and deafness,[3,5,6] which is directed toward answering the above question and providing controlled comparisons between different tactile speech-communication systems, has focused on discrimination and identification of nonsense syllables, comprehension of sentences (constructed from a very limited, previously learned set of isolated words), and the development of efficient training procedures. Roughly speaking, our preliminary results with these subjects indicate that only relatively small amounts of training are required to enable inexperienced subjects to discriminate nonsense syllables with an accuracy comparable to that achieved by the experienced Tadoma users and that the most difficult task in learning Tadoma for these subjects concerns the comprehension of running speech. Even for this task, however, we have found no evidence that learning Tadoma is more difficult than learning a foreign language. A project is now being initiated in which six normal subjects will spend roughly 5-10 hours/week for a duration of 1-2 years attempting to learn Tadoma.

b. Development of Artificial Display Systems

In addition to studying the performance achieved with the Tadoma method, considerable effort has been directed toward the development of artificial encoding and display systems. Until recently, the only such systems considered have been those that employed a frequency-to-place encoding scheme (i.e., decomposing the speech signal into spectral bands and presenting different frequency bands to

different locations on the skin) and a display based on the transducer portion of the optacon.[7,8]

One project is concerned with the development of a new stimulator array.[9] Although the optacon has been used for preliminary experiments, it has many important limitations (i.e., it can only be applied to the finger, the vibrations cannot be controlled in amplitude on an individual basis, etc.). In order to provide increased flexibility and to help us separate out limitations imposed by the particular encoding scheme from limitations imposed by the particular transducer system, we have constructed a new computer-controlled vibrotactile array. This array, which is modeled after an array developed at Princeton,[10] consists of a rectangular configuration of 81-256 vibratory stimulators (piezoelectric bimorph benders) driven synchronously by linear high-voltage transistor-amplifiers under computer control. As in the Princeton system, the array of stimulators is mounted in such a way that it can conform readily to irregular skin surfaces and can be clamped rigidly to maintain a given conformity. Also, stimulator density can be easily changed by substituting sets of bimorphs within the array. Patterns on the display are created on a frame-by-frame basis by specifying the amplitude of excitation applied to each vibrator on an individual basis. Also, excitation wave shape and frame duration can be specified for each frame. To achieve this degree of flexibility, it was necessary to provide a high degree of hardware parallelism (256 digitally programmable high-voltage amplifiers for driving the bimorphs), as well as a sophisticated control system for the high data rates required (10^5 bytes/sec) to specify complex patterns at peak frame rates.

A second project is concerned with the creation of software for the study of different types of encoding and display schemes. For example, we have developed an algorithm for displaying acoustic frequency in terms of a textural variable (spatial frequency) rather than a spatial variable. Similarly, we have developed a linear-prediction scheme to convert acoustical waveforms to representations of vocal-tract area functions (plus voicing detection) for display on our stimulator arrays. Encoding by use of the vocal-tract area function is of interest both because of the low bit rate associated with this type of system (as compared to a channel vocoder) and because of the direct tie to the speech-articulation process.

A third project is concerned with the development of a synthetic Tadoma

system. In this system, the listener places his hand on an artificial face that is driven by a sensor array (via computer control) mounted on the talker's face. The initial goal is to create a system that will produce speech reception results similar to those produced with "real" Tadoma. Once this goal has been achieved, the system will be used to gain further insight into Tadoma by altering different components of the system and examining the effects of these alterations on speech reception (i.e., altering the inputs, the processing, and/or the display). Initial work on this project has focused on exploration of techniques for construction of the artificial face (the most difficult task in the project). In this work, we have assumed that all the necessary input signals to the display are available from the sensor array and that the problem is to make use of these signals to drive the artificial face in an appropriate manner. Furthermore, we have assumed that the main problem in the construction of the face concerns the accurate reproduction of lip movement, since we believe that the reproduction of laryngeal vibration, breath flow, and (if necessary) jaw movement can be achieved using relatively standard devices. In the design of the lip-movement system now under consideration, a rubberlike material is used to mold the "lips" and surrounding "skin" and to obtain internal cavities of various sizes and shapes. The position and movement of the lips is then controlled by the air pressure in the internal cavities (which vary in shape as the air pressure is varied). Current work on this lip-display system is focused on the selection of material, the selection of the method for controlling airflow, and the cavity design problem.

Further engineering effort has been directed toward the design of interfaces and software for computer control of the various display systems. For example, we have designed a new interface for the optacon to ensure synchronous generation of display frames, reduce system overhead, and simplify the programming required to specify patterns. We have also developed a general-purpose enhancement to standard DMA controllers to permit real-time clock-controlled input and output transfers to occur with minimal computer loading. This interface design will be used for transfers to the new tactile array system (which requires only output transfers) as well as to the artificial face system (which will ultimately require both input and output transfers). In addition, we have begun to develop the control subsystem of the new tactile array system. This hardware will translate

computer-generated specifications of tactile stimulus patterns into timing and data-flow signals that can be applied to the DAC's and amplifiers of the display.

Finally, we are beginning to formulate a program of psychophysical experiments concerned with the determination of appropriate schemes for displaying time-varying functions to the tactile sense.[11] Independent of exactly how these functions are derived from the speech signal (e.g., by taking amplitude spectra, vocal-tract area functions, etc.), the problem of how to best display these functions is clearly fundamental. The above-described engineering efforts concerned with the development of the new vibrotactile array and the various computer programs and interfaces provide us with a facility that is highly suitable for this purpose.

c. Comparison of Artificial Systems with Tadoma

Although the overall speech-reception results obtained with deaf-blind subjects and the Tadoma Method appear to be substantially superior to results obtained with artificial systems, one cannot automatically conclude that the Tadoma Method is superior. In particular, such a conclusion ignores the vast differences in training received by the Tadoma users and the subjects tested with the artificial systems. Clearly, a rigorous comparison requires the use of equivalent subjects and equivalent training.

In a preliminary experiment comparing a frequency-amplitude display on the optacon to Tadoma,[12] 32 pairs of consonants (contrasting voicing, manner, and place) were used in a CV syllable discrimination test with normal, relatively inexperienced subjects. The consonant contrast was held fixed throughout a run, but the vowel was varied randomly (over the set /i,a,u/) from trial-to-trial. All stimuli were presented "live voice" and nontactile cues were eliminated by the use of a blindfold and masking noise. The results of these discrimination tests showed Tadoma to be substantially superior with respect to contrasts of voicing and place, but roughly equivalent to the artificial system for contrasts of manner.

The fact that one must be careful in generalizing this result, however, is indicated by a comparison between our Tadoma results and those reported for the MESA.[13] According to our analysis,[3] Tadoma is superior with respect to the identification of consonants, but inferior with respect to the identification of vowels. Furthermore, within the consonant category, although Tadoma produces

superior performance for plosives and nasals, it produces roughly comparable performance for fricatives. Overall, we see no evidence that this artificial display is substantially inferior to Tadoma for the transmission of segmental elements.

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(XXVII. COMMUNICATIONS BIOPHYSICS)

5. MUSICAL PITCH

National Institutes of Health (Grant 2 R01 NS11680)

Adrian J.M. Houtsma

The overall objective of this research is to gain understanding of the auditory processes that underlie musical pitch sensations evoked by complex sounds. Research effort has been focused on three projects.

a. Pitch Perception of Harmonic Tone Complexes

Evaluation of modern pitch theories, using a musical interval recognition paradigm, was continued.[1] Attention was focused on the influence of the intensity relation between the pure-tone components of two-tone complexes on the ability of subjects to track the missing fundamental.[2] Dichotically presented two-tone complexes with interaural intensity differences of 0, ±10, and ±20 dB and frequencies nf_0 and $(n+1)f_0$ were used to play melodic intervals to be identified. Confusion matrices were determined for each intensity relation and several values of n. Two of the theories studied[3,4] make specific predictions of expected confusions. A third "analytic perception" model, which assumes that the pitch of a complex tone is largely determined by the frequency of the loudest partial, was also tested. Results so far seem to indicate a stronger correlation between the confusion data and the analytic model than between the data and confusions predicted by any of the current theories.

b. Pitch Perception of Amplitude-Modulated Noise

Periodically modulated AM noise has traditionally been regarded as being devoid of spectral clues, and pitch sensations evoked by these sounds have been explained on a temporal basis. Short-term spectra of such signals, however, do contain possibly relevant pitch information. Two models were developed, one based on temporal processing, the other on short-term spectral processing. They were quantitatively tested with experimental data on musical interval recognition using lowpass noise modulated by a sine wave, square wave or a periodic narrow pulse. The empirical data are generally more consistent with the temporal model than with

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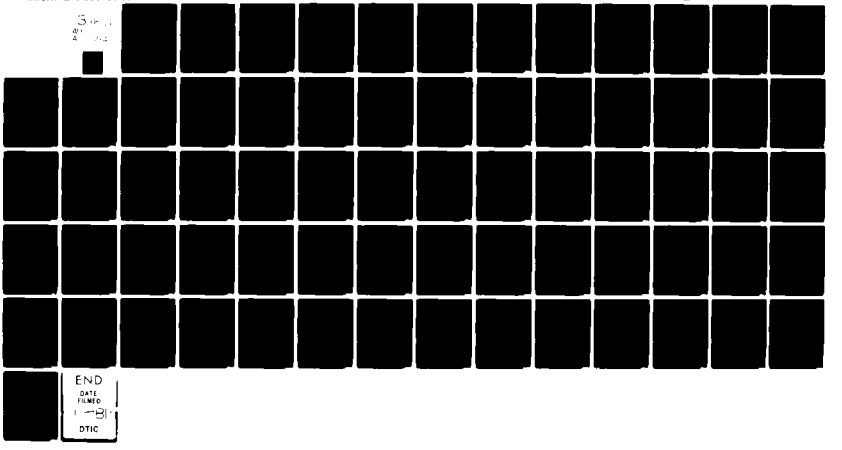

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the spectral model. There is, however, some evidence for both types of processing in the auditory system, where temporal processing dominates in the high-frequency channels and short-term spectral processing in the low-frequency channels. Details of this study are available in Houtsma, Wicke, and Ordubadi.[5]

c. Induced Pitch Shifts for Pure and Complex Tones

According to the "virtual pitch theory" by Terhardt,[4] complex tone pitch is derived from spectral pitch images of the partials, rather than from the partial frequencies. It has also been found experimentally that a pure-tone pitch image can be changed by as much as 5% when the tone is partially masked by lowpass noise.[6] Noise-induced shifts in the pure-tone pitches of partials and in the complex-tone pitch of the missing fundamental were studied through pitch matches between partially masked one- and two-tone test stimuli and an adjustable periodic pulse comparison stimulus. Both monotic and dichotic signal presentations were used. The results show a systematic dependence of the pure-tone pitch on the intensity of the masking noise, which is in qualitative and quantitative agreement with other results found in the literature. The complex tone pitch, however, showed a considerably smaller variation with noise level than expected if this pitch were derived from the respective partial (pure-tone) pitches. This finding is inconsistent with the serial processing idea of the virtual pitch theory, but suggests that pure-tone pitch and complex tone pitch are processed via separate parallel channels, the former based on spatial encoding and the latter on temporal encoding. Details are available in Houtsma.[7]

d. Pitch Discrimination of Pure and Complex Tones in Masking Noise

Work has begun on the study of pitch discrimination for pure tones, complex tones, and synthetic speech vowels in the presence of masking noise. A 2-interval forced-choice adaptive procedure is used to measure pitch jnd's as a function of masking noise intensity. The results are used to compare pitch discrimination sensitivity of human observers to that of current pitch extractor algorithms which are used for analysis and synthesis of speech.

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XXVII. COMMUNICATIONS BIOPHYSICS

C. Transduction Mechanisms in Hair Cell Organs

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National Institutes of Health (Grant 2 ROl NS11080)

Lawrence S. Frishkopf, Charles M. Oman

Our objective is to understand the mechanisms of transduction in the phylogenetically related auditory, vestibular, and lateral line organs in response to mechanical stimulation. In all of these organs the receptors are ciliated hair cells.

Goals during the past year have been (1) to measure the displacement of the cupula in the skate semicircular canal as a function of applied force, resulting in a description of cupula motion in terms of a simple elastic model; (2) to determine the influence in this system of canal shape on endolymph flow and cupula motion; and (3) to begin studies of mechanical properties of hair cell cilia in a simple auditory organ, the basilar papilla of the alligator lizard.

1. STIFFNESS COEFFICIENT OF THE CUPULA IN THE SEMICIRCULAR CANAL OF THE SKATE*

Lawrence S. Frishkopf, Richard D. Kunin

Cupula displacements have been measured in the semicircular canal of the skate, Raja erinacea, under known loads. The cupula stiffness coefficient — the ratio of applied torque to angular displacement — has thereby been directly determined.[1] All procedures were carried out in artificial skate perilymph.[2] The excised labyrinth was dissected to expose the ampulla which was cut from the canal with fine iris scissors. The ampulla was trimmed to enlarge the openings at both ends; contact with the cupula was carefully avoided. Attachment of the cupula at both the crista and at the vault of the ampulla and the integrity of the hair cell cilia were assessed using Nomarski interference contrast optics. Preparations which by these

criteria appeared undamaged were studied further under the Nomarski microscope.

Small pieces of aluminum foil were placed upon the cupula and resulting cupula displacements at one or more points were measured. Displacements were in the range from 10 to 160 micrometers, large compared to estimates of the physiological upper limit (3-5 micrometers) in the same species.[3] Displacements at different points were consistent with the notion that the cupula moves as a unit about an attachment region at the crista. The location of the foil allowed estimation of the torque about the crista and thereby determination of the stiffness coefficient of the cupula. In some preparations several pieces of foil were placed upon the cupula and thereby successive increments of displacement were measured; the stiffness coefficient increased as additional load was placed on the cupula. Measured stiffness coefficients were between 4×10^{-4} and 4×10^{-3} dyne-cm/rad in different preparations. These values are consistent with those that have been inferred in other species by less direct means.[4-6]

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2. THE INFLUENCE OF AMPULLA, DUCT, AND UTRICULAR SHAPE ON SEMICIRCULAR CANAL ENDOLYMPH FLOW DYNAMICS

Charles M. Oman, Edward N. Marcus

Theoretical descriptions of endolymph flow and cupula motion in the semicircular canal have traditionally been made employing a simple model in which the entire membranous canal is represented as a hollow, thin torus. The canal lumen is thus assumed to be of constant, circular cross section. The traditional model (van Egmond et al., 1949) predicts that angular flow displacement about the center of the torus is related to head angular acceleration by a second-order differential equation with two coefficients. However, the size of the lumen of an actual canal does vary significantly in the ampulla and utricle. In the past, numerous authors have proposed — with no detailed theoretical justification — that the two-coefficient van Egmond/Groen model may be adjusted for the presence of the ampulla and utricle simply by neglecting the effects of flow drag in these segments (Money et al., 1971; McLaren, 1977) or by increasing the moment of inertia assumed for the fluid ring (Mayne, 1965; Oman and Young, 1972; Curthoys et al., 1977).

Oman (1979), recently employed a model with more complex geometry in which the duct and utricle were represented as separate segments, each having a different (elliptic) cross section and arbitrary length. Oman demonstrated that in this case fluid flow is more accurately described by a second-order differential equation with three coefficients, rather than by the traditional two-coefficient model. It was shown that the short time constant of the canal should be relatively independent of the fraction of the canal torus occupied by the utricle and ampulla, but that the amount of cupula motion produced by head movement should be heavily influenced by this factor. Preliminary numerical estimates of semicircular canal short time constant and volume-displacement gain were made using anatomical data available in several species, including man. However, detailed anatomical measurements describing the shape of the ampulla and utricle were not available.

During the past year, we have extended our theoretical modelling approach to describe Newtonian endolymph flow for the yet more general case where the shape of the canal lumen varies continuously in a gradual fashion through the duct, ampulla,

and utricle, and where the central axis of the canal lumen lies in a single plane, but may deviate from the commonly assumed circular form. Analytical expressions for the three coefficients of the resulting second-order differential equation for fluid flow have been determined. The coefficients were shown to depend strongly on the average of the inverse cross-sectional area of the canal lumen and the average of the inverse cross-sectional area squared, taken around the entire canal. To investigate the behavior of these mathematical functions for an actual case, an optical technique was devised which permitted the necessary dimensional measurements to be made in the duct, ampulla, and utricle of a fixed, dissected, horizontal semicircular canal duct of the skate, Raja erinacea. Our numerical results confirm the conclusions reached using Oman's simpler two-segment model. However, the new more general analytical model provides useful theoretical insights. We conclude that, in most cases, the three coefficients of the differential equation describing canal fluid flow are dominated by the influence of narrow-duct cross-sectional area and its shape, and the fraction of the circumference of the canal occupied by the duct.

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XXVII. COMMUNICATIONS BIOPHYSICS

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William M. Siebert

Included under this heading are a variety of topics in biophysics, physiology, and medical engineering. Many of these are individual projects of students supported by a training grant from the National Institutes of Health.

XXVIII. NEUROPHYSIOLOGY

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1. TECTAL STUDIES OF AMBYSTOMA

National Institutes of Health (Training Grant 5 T01 EY00090)
Bell Laboratories (Grant)

Edward R. Gruberg, William Harris
[William Harris is with the Department of Neurobiology, Harvard Medical School, Boston, Mass.]

In an earlier study Gruberg and Solish showed that salamander somatosensory spino-tectal fibers took the same course and ended in the same layer of the intermediate tectal neuropil as 5-hydroxytryptamine (5-HT or serotonin) fibers as seen by Falck-Hillarp fluorescence. In order to determine whether the spino-tectal fibers are themselves serotonergic, we have carried out anatomical, biochemical, genetic and physiological tests. By using a specific 5-HT fiber poison, 5,7-dihydroxytryptamine (5,7-DHT), we have been able to abolish electrically recorded contralateral somatosensory units while the overlying visual units appear normal. 5,7-DHT poisoning also abolished 5-HT fluorescence in the intermediate tectal neuropil.

Genetically eyeless salamanders, or normal salamanders bilaterally enucleated early in development, have a shift in their somatosensory input to the superficial tectum. There is the same shift in Falck-Hillarp serotonin fluorescence. This shift is not due to a sprouting of 5-HT fibers. With the use of high-performance liquid chromatography, we have found the same amount of tectal serotonin in normal and eyeless salamanders.

We have traced the origins of the spino-tectal cells by using HRP tectal

injections. A majority of these cells lie in a thin lamina on the ventral border of the spinal gray. This is the same layer where serotonin cell bodies are also found. In addition, we have verified the results obtained with Falck-Hillarp fluorescence by injecting ^{3}H-serotonin into the tectum and subsequently carrying out radioautography.

Collectively, these results strongly suggest that at least some somatosensory fibers in the salamander tectum are serotonergic.

2. THE BASAL OPTIC SYSTEM

National Institutes of Health (Training Grant 5 T01 EY00090)
Bell Laboratories (Grant)

Edward R. Gruberg, Keith Grasse
[Keith Grasse is with the Department of Psychology, Dalhousie University, Halifax, Nova Scotia.]

We have begun experiments to investigate the anatomy and physiology of the basal optic area (BOA) in the frog. The BOA in the ventral tegmentum receives a direct input from the retina, consisting of the largest diameter fibers found in the optic nerve.

With the animal on its back and using a ventral penetration through the upper mouth, we have been able to record routinely single units in the BOA. Most units are directionally sensitive to moving stimuli. So far we have found two classes of units: those responsive preferentially to vertical moving stimuli and those to horizontal moving stimuli. A wide variety of sizes and shapes of stimuli elicit responses. Vertical units increase firing to either slow upward movement or slow downward movement; the opposite direction gives a null response. Horizontal units increase firing either to slow naso-temporal movement or to slow temporo-nasal movements. They, too, give null response in the opposite direction. All these units yield broad tuning curves of response vs direction of movement. The best response is obtained for most units when stimuli are moved with angular velocity in the range of 0.1° to 1°/sec.

We have also begun an HRP study of the connections of the BOA. Since the target

region is very small, we have developed a method for delivering volumes of 1/2 nanoliters or less of HRP solution. We have found ipsilateral projections to the BOA arising from three principal areas: the posterolateral tegmental field, the posterior nucleus of the thalamus, and a wide extent of the ventral thalamus, particularly in the anterior part. So far, we have found no clear contralateral input.

Publications

Gruberg, E.R., E.A. Newman, and P.H. Hartline, "The Python and the Rattlesnake: A Comparison of Infrared Trigemino-Tectal Techniques," Abstracts for Society for Neuroscience Meeting, Atlanta, Georgia, 1979, p. 708.

Gruberg, E.R., E. Kicliter, E.A. Newman, L. Kass, and P.H. Hartline, "Connections of the Tectum of the Rattlesnake Crotalus viridis: An HRP Study," J. Comp. Neurol. 188, 31-42 (1979).

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3. RETINAL OPERATORS THAT NULL OUT RIGID 3-SPACE TRANSLATIONS

Bell Laboratories (Grant)

Michael H. Brill

Suppose an artificial planar retina of photosensors receives (via optical elements) an image of light reflected from a matte coplanar array of reflectances. Suppose the reflecting surface is parallel to the retina, is uniformly illuminated, and undergoes rigid translation in 3-space — a motion that is arbitrary but constrained so the edge of the surface never passes over the retina. Such a situation might be encountered by an airborne camera looking directly down at flat terrain — neglecting the earth's curvature. Without prior knowledge (such as ground speed in the above application), how can the retina detect that no motion other than a rigid translation is going on?

One solution to this kind of problem, proposed by Pitts and McCulloch,[1] is to generate all possible translated versions of the initial image internally, and match

them to the actual image as it evolves in time. If the instantaneous image is tolerably close to any translated version of the initial image, then it is construed as that translated version. One problem with this method is that parts of a translating image newly emerging into view of the retina are not matchable to a translated version of the initial image. This is rather easily solved by arranging that each instantaneous image be compared to the previous image rather than to the first image, and ignoring the edge of each image in the comparison. A more difficult problem is to do all the shifting and comparing in real time.

We have developed another method, not so general but easier computationally: The retina performs a nonlinear differential operation on the point-of-view-corrected light-energy image $h(x,y,t)^*$ such that the result of the operation is zero if the image is due to light reflected from a matte plane parallel to the retina undergoing 3-space translation. The differential operator is of order three, and is evaluated far enough away from the retinal edge so as not to incur artifacts. The operator is derived below.

First, the form of $h(x,y,t)$ is derived for the motion in question.

In setting up the geometry, the following specifications are made without loss of generality: In the 3-space (Cartesian coordinates η,ξ,ζ), the retina is at $\eta = 1$, and a 3-space point is represented on the retina by conical projection through (0,0,0). Retinal rectangular coordinates (x,y) are chosen so that the x axis is parallel to the ξ axis in the 3-space, and the y axis is parallel to the ζ axis.

Then the projected image of a point (η,ξ,ζ) on the retina is the point

$$x = \frac{\xi}{\eta}, \qquad y = \frac{\zeta}{\eta}. \tag{1}$$

Suppose these coordinates represent a point on an object at time t that had at $t = 0$ the coordinates $(\hat{\eta},\hat{\xi},\hat{\zeta}) = (\eta + \alpha, \xi + \beta, \zeta + \gamma)$. Then the image of the object point at $t = 0$ was at the retinal point

$$\hat{x} = \frac{\xi + \beta}{\eta + \alpha}, \qquad \hat{y} = \frac{\zeta + \gamma}{\eta + \alpha}. \tag{2}$$

Here α, β, and γ are unspecified functions of time t.

The ensemble of viewed points (η,ξ,ζ) lies on a plane whose equation at $t = 0$ is $\eta = s$ (where s is a constant). All these points are translated by the same vector (α,β,γ) at time t, whence

$$(\hat{x},\hat{y}) = \left(\frac{sx + \beta}{s + \alpha}, \frac{sy + \gamma}{s + \alpha}\right). \tag{3}$$

Suppose at time t the viewed-plane point (η,ξ,ζ) reflects light power $I(\xi,\zeta,t)$ uniformly through solid angle 2π. The retina is presumed to receive all the light from this point at $(x,y) = (\xi/\eta, \zeta/\eta)$, and the power received is

$$H(x,y,t) = \frac{I(\xi,\zeta,t)}{2\pi r^2} \cos\theta,$$

where r is the distance from (η,ξ,ζ) to $(1,x,y)$, and θ is the angle the light path makes with the normal to the retinal plane. If the retinal image is real, then

$$\cos\theta = \frac{\eta}{\sqrt{\eta^2 + \xi^2 + \zeta^2}} = \frac{1}{\sqrt{1 + x^2 + y^2}}$$

$$r^2 = (1+\eta)^2 + (x+\xi)^2 + (y+\zeta)^2 = (1+\eta)^2\,(1+x^2+y^2).$$

Thus

$$H(x,y,t) = \frac{I(\xi,\zeta,t)}{2\pi(1+\eta)^2\,(1+x^2+y^2)^{3/2}}. \tag{4}$$

Translation of the viewed plane corresponds to the identification

$$I(\xi,\zeta,t) = I(\xi+\beta,\zeta+\gamma,0) = I(\hat{\xi},\hat{\zeta},0).$$

From Eq. 4,

$$\begin{aligned} I(\xi,\zeta,t) &= 2\pi H(x,y,t)(1+\eta)^2\,(1+x^2+y^2)^{3/2} \\ I(\hat{\xi},\hat{\zeta},0) &= 2\pi H(\hat{x},\hat{y},0)(1+\hat{\eta})^2\,(1+\hat{x}^2+\hat{y}^2)^{3/2}. \end{aligned} \tag{5}$$

If one defines at each t the point-of-view-corrected image

$$h(x,y,t) = H(x,y,t)(1+x^2+y^2)^{3/2},$$

then

$$h(x,y,t) = \frac{(1+\hat{\eta})^2}{(1+\eta)^2}\, h(\hat{x},\hat{y},0) \equiv \frac{(1+\hat{\eta})^2}{(1+\eta)^2}\, f(\hat{x},\hat{y}). \tag{6}$$

From the initial condition $\eta = s$, Eq. 3, and the condition $\hat{\eta} = \eta + \alpha$, it follows that

$$h(x,y,t) = \left[1 + \frac{\alpha}{1+s}\right]^2 f\left(\frac{sx+\beta}{s+\alpha}, \frac{sy+\gamma}{s+\alpha}\right). \tag{7}$$

Now define $a \equiv s/(s+\alpha)$, $b \equiv \beta/(s+\alpha)$, $c = \gamma/(s+\alpha)$, and rewrite Eq. 7 as follows:

$$h(x,y,t) = \left[1 + \frac{s}{1+s}\left(\frac{1}{a} - 1\right)\right]^2 f(ax+b,\ ay+c). \tag{8}$$

This is the general form of h for the motion in question.

There are two important limits in which h takes particularly simple forms: When $s \ll 1$ (the microscopic limit), $h(x,y,t) = f(ax+b,\ ay+c)$; and when $s \gg 1$ (the telescopic limit), $h(x,y,t) = (1/a^2)\, f(ax+b,\ ay+c)$. For both of these forms, we now derive specific relations between the partial derivatives of h and a,b,c. Henceforth $\dot{a}$ will be the time derivative of a, and so on; h_x will be the partial derivative of h with respect to x, and so on; and f_1 will be the partial derivative of f with respect to its first argument, and so on.

In each limiting case, the strategy will be to solve for pure functions of time in terms of partial derivatives of h (readily computed by the retina), and then take spatial derivatives of these functions of time. These derivatives will be zero when h has the desired form. However, the same functions of the partial derivatives of h will not have this property when h does not have the desired form; their nonzero spatial derivatives will cue targets moving on a rigid background.

a. Microscopic Limit [h(x,y,t) = f(ax+b, ay+c)]

We begin by computing all first partial derivatives of h to get expressions that explicitly involve a, b, c, and their first time derivatives:

$$h_x = af_1; \qquad h_y = af_2$$
$$h_t = (\dot{a}x+\dot{b})f_1 + (\dot{a}y+\dot{c})f_2. \tag{9}$$

By removing f_1 and f_2 from these equations, and defining the pure-time functions $A = \dot{a}/a$, $B = \dot{b}/a$, $C = \dot{c}/a$, one obtains

$$h_t = A(xh_x + yh_y) + Bh_x + Ch_y. \tag{10}$$

As desired, this equation relates the partial derivatives of h — computable from the image — to pure-time functions characteristic of the motion. To generate enough equations at each point (x,y) to solve for A,B,C, we differentiate Eq. 10 with respect to x and y, thereby getting three linear equations in A,B,C with coefficients being functions of the partial derivatives of h:

$$h_t = A(xh_x + yh_y) + Bh_x + Ch_y$$
$$h_{tx} = A(xh_{xx} + yh_{xy} + h_x) + Bh_{xx} + Ch_{xy} \tag{11}$$
$$h_{ty} = A(xh_{xy} + yh_{yy} + h_y) + Bh_{xy} + Ch_{yy}.$$

This set of equations can be solved for A, B, and C (e.g., by Cramer's rule). A, B, and C are then functions of the partial derivatives of h whose gradients can be evaluated for any h. A nonzero gradient is a diagnostic for image changes that are not rigid translations in 3-space.

Do translating planes that are parallel to the retina produce the only visual inputs h that are nulled out by the above operators (which we henceforth call $\vec{Z}$)? We have not been able to determine yet whether these geometrical constraints are the only ones generating h(x,y,t) = f(ax+b, ay+c). One can show, however, that this form for h is the only one satisfying $\vec{Z}h = 0$.

[Proof: First, note that Eqs. 11 represent the general first integration of $\vec{Z}h = 0$, but A, B, and C are now arbitrary functions of time, not necessarily deriving from a, b, and c. Second, note that a solution of Eq. 10 (the first of Eqs. 11) automatically solves the other two equations. Thus the only PDE to be solved is Eq. 10. To show the uniqueness of the form of Eq. 8 as a solution to Eq. 10, first construct from the first-integrated time functions A,B,C the functions a_1, b_1, c_1 such that

$$A = \frac{\dot{a}_1}{a_1}, \qquad B = \frac{\dot{b}_1}{a_1}, \qquad C = \frac{\dot{c}_1}{a_1}.$$

Functions with this property are

$$a_1 = e^{\int A\, dt}, \qquad b_1 = \int a_1 B\, dt, \qquad C_1 = \int a_1 C\, dt.$$

Then Eq. 10 becomes

$$a_1 h_t = \dot{a}_1(xh_x + yh_y) + \dot{b}_1 h_x + \dot{c}_1 h_y. \tag{12}$$

Finally, change variables in the above differential equation to the new variables $T = t$, $X = a_1 x + b_1$, $Y = a_1 y + c_1$. This transforms the partial derivatives to

$$\begin{aligned} h_t &= h_T + h_X(\dot{a}_1 x + \dot{b}_1) + h_Y(\dot{a}_1 y + \dot{c}_1) \\ h_x &= h_X a_1; \qquad h_y = h_Y a_1. \end{aligned} \tag{13}$$

Substitution of Eqs. 13 into Eqs. 12 yields the condition $h_T = 0$, whence h depends only on $X = a_1 x + b_1$, and $Y = a_1 y + c_1$.]

Equation 10 is a familiar differential form: $x\frac{\partial}{\partial x} + y\frac{\partial}{\partial y}$ is the Lie generator of isotropic dilation; $\frac{\partial}{\partial x}$, $\frac{\partial}{\partial y}$ are the Lie generators of translation in x and y, respectively. Newman and Demus[2] (in a program of research that paralleled our own) also parametrized motion with the Lie group formalism, including a generator $x\frac{\partial}{\partial y} - y\frac{\partial}{\partial x}$ for rotations as well as those above. One might note that, since they were dealing with a missile-tracking application, their dilation operator on h

might more appropriately have been replaced by $xh_x + yh_y - 2h$ as in (b) below.

Instead of differentiating their analogue of Eq. 10 to provide the necessary equations to solve for the pure-time variables, Newman and Demus generated nine equations for each retinal point by evaluating their analogue of Eq. 10 at the point itself and at the eight points surrounding it.

This illustrates an important freedom in our method, to be optimized in pattern-recognition applications: The differentiation operations generating the second and third of Eqs. 11 can be replaced by any two independent nonidentity spatial linear operations (such as convolutions). Optimizing these operators may reduce the noise attendant in digital computations approximating the derivative. Another strategy for noise suppression is to take the gradient of nonlinear functions $\phi(A,B,C)$ rather than of the pure-time functions A,B,C themselves. This freedom is also allowed in our formalism.

A final word should be said about the cases in which the inversion of Eq. 11 is impossible (e.g., when $h_x = h_y = 0$, which is the condition of a local spatial uniformity). If a determinant test shows that Eq. 11 is not invertible at a point, the operator at that point must be immediately zeroed and the inversion avoided. A,B,C can then be interpolated in the singular region. This circumvents the singularity, and still permits the advancing (or retreating) edge of a target moving on a uniform background to yield nonzero values for $\vec{Zh}$. Thus the operator can function as a target spotter even when $\vec{Zh}$ is zeroed where Eq. 11 is not invertible.

b. Telescopic Limit $\left[h(x,y,t) = \frac{1}{a^2} f(ax+b, ay+c)\right]$

In a manner analogous to that of the microscopic limit, one can show that

$$h_t = A(xh_x + yh_y - 2h) + Bh_x + Ch_y, \tag{14}$$

where $A = \dot{a}/a$, $B = \dot{b}/a$, and $C = \dot{c}/a$. Operating on this equation with two independent spatial linear operators allows one to solve for A,B,C for each picture element, as before. The proof of the uniqueness of the form $\frac{1}{a^2} f(ax+b, ay+c)$ as a solution to Eq. 14 remains to be completed.

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Footnotes and References

*If the retinal plane is one unit of distance from the projection center, h is the light-energy distribution on the retina, multiplied by $(x^2 + y^2 + 1)^{3/2}$ to correct for the anticipated distance and cosine errors if the viewed scene were a matte plane parallel to the retina.

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4. APPARENT REFERENCE-FRAME PARADOX IN GENERAL RELATIVITY

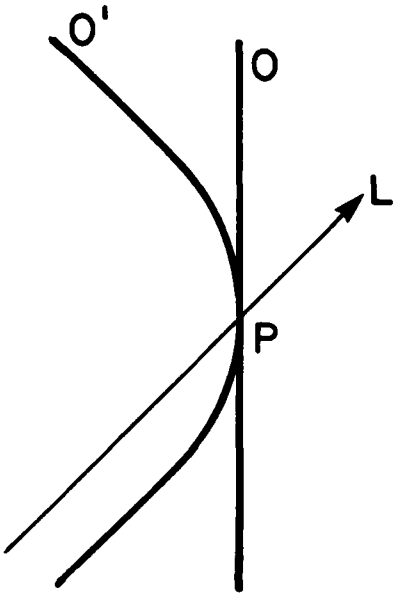
Bell Laboratories (Grant)

Michael H. Brill

Computations connecting General Relativity with its three fundamental tests – perihelion advance of Mercury, light bending, and red shift, all in the sun's gravity field – make no note of the noninertial status of the earthbound reference frame.[1-3] How would the measurements change if the observer were stationary and freely falling at the surface of the earth? When we examined the problem of transforming between measurements of inertial and noninertial observers in a uniform gravity field (a case much simpler than the true gravitational field of the earth), the following apparent paradox arose:

The strong Principle of Equivalence in General Relativity states that observer accelerations are locally indistinguishable from gravity fields. (This is to be contrasted with a less stringent interpretation – the weak Principle of Equivalence – which asserts the equivalence of inertial and gravitational mass.) If we adopt the interpretation of Ohanian[4] (and others) that global departures from strong equivalence are due to gravity gradient effects (tidal forces), then uniform gravity fields should display a global strong equivalence, since a uniform field has zero gradient.

On the other hand, reference frames in General Relativity are commonly interpreted as local Lorentz coordinate systems.[5] Suppose in flat space-time the world lines of inertial observer O and accelerating observer O' are tangent to each other at point P, and that both observers see a light at P (see diagram). If O and O' adopt the same local Lorentz frame at P, they should record the same measurements of L at P. But the Principle of Equivalence says O' should find his acceleration the same as a uniform gravity field, through which light L should appear frequency-shifted relative to the measurement made by O. In view of these contradictory arguments, does O make the same frequency measurement as O' on light L?



It would seem that if O and O' make identical measurements at P, then this would forbid interpretations of the Principle of Equivalence stronger than the equivalence of inertial and gravitational mass. If O and O' make different measurements at P, then it would seem that reference-frame transformations are not the same as coordinate transformations, no matter how locally these transformations are constrained.

One aspect of the problem not heretofore discussed is the motion of the light source as seen by O and O'. When O' sees L at P, he also construes that the light source was moving with respect to him at the time of emission of L from the source. It is possible that the Doppler shift of the light as seen by O' exactly cancels the gravitational frequency shift demanded by the strong Principle of Equivalence, and thus renders identical the measurements of L by O and O'. We are now addressing this possible resolution of the paradox, and are discovering that an important unresolved consideration is the coordinate system in which the "equivalent" gravity field is expressed.

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3. M.H. Brill, "Observer Reference Frames in General Relativity," AAAS General Meeting (poster session), San Francisco, January 3-8, 1980, Abstract volume, p. 135.

4. H.C. Ohanian, "What Is the Principle of Equivalence," Am. J. Phys. 45, 903-909 (1977).

5. C. Misner, K. Thorne, and J.A. Wheeler, Gravitation and Cosmology (Wiley, New York, 1972), Chap. 6.

5. COMPUTER-SIMULATED OBJECT-COLOR RECOGNIZER

Bell Laboratories (Grant)

Michael H. Brill

If a spatially diffuse illuminant with spectral power distribution $I(\lambda)$ is incident on a set of coplanar matte reflectors with spectral reflectances $r_i(\lambda)$, a trichromatic visual system (artificial or natural) will represent the reflected lights as tristimulus values

$$Q_{ij} = \int I(\lambda)\, r_i(\lambda)\, q_j(\lambda)\, d\lambda, \tag{1}$$

where $q_j(\lambda)$ (j=1,2,3) are the spectral sensitivities of the eye.

If the visual system is an object-color recognizer, it must compute functions of Q_{ij} that are invariant with respect to spectral changes in $I(\lambda)$. What is computed will be related to object spectral reflectances and not to the illuminant spectral power distribution (SPD).

More particularly, it is desired to find a function of Q_{ij} that is invariant with respect to interchange of illuminants in a spectral equivalence class (characteristic of naturally occurring lights). Implicit in this treatment is a restriction on the allowed reflectance spectra, and possibly also on the spectral sensitivities of the photosensor.

In previous work,[1] we noted that tristimulus volume ratios are illuminant-invariant if the spectral reflectances are linear combinations of three particular functions of wavelength. In this case the equivalence class of illuminant SPDs is almost unrestricted. It is required only that noncoplanar object-color tristimulus vectors remain noncoplanar when the light is changed. We note that the three reflectance-spectrum basis functions need not be "known" by the recognizer, because tristimulus volume ratios will in any case be illuminant-invariant.

On the basis of this principle, we have designed (in computer simulation) an object-color recognizer,[2] and compared its performance with that of a recognizer computing scaled-integrated reflectances as in the work of McCann et al.[3]

The general recognizer framework is shown schematically in Fig. XXVIII-1. The sensor turns reflected light spectra $I(\lambda)\ r_i(\lambda)$ into tristimulus vectors $\underline{Q}_i$ via sensors $q_j(\lambda)$. (Spectra for lights $I(\lambda)$ and pigments $r_i(\lambda)$ are tabulated and multiplied in our computer simulation.) By using the reflected-light tristimulus vectors from a set of known reflecting objects (known in the sense of being color-named ahead of time), a transformation is derived for removing contingency on the illuminant spectrum $I(\lambda)$. The three-vectors $\underline{\alpha}_i$ emerging from this transformation we call object-color three-vectors. They are compared (via a Euclidean distance measure) with a set of stored template three-vectors $\underline{\alpha}_i^{(0)}$ corresponding to the same reflectors under a calibration light $I_0(\lambda)$. All the $\underline{\alpha}_i^{(0)}$ are associated with distinct color names. The template closest to any given object-color vector is assigned as the putatively identified color, and is given the color name of that template. Identification scores are computed as the number of correct pairings of $\underline{\alpha}_k$ with $\underline{\alpha}_i^{(0)}$, divided by the total number of pairings.

The transformation used for comparison with the volumetric method was a streamlined version of the Retinex theory[3]: In a particular tristimulus basis, the illuminant-invariant quantities are taken to be "scaled integrated reflectances"

$$\alpha_{ij} = \frac{Q_{ij}}{Q_{j\,max}} = \frac{\int I(\lambda)\ r_i(\lambda)\ q_j(\lambda)\ d\lambda}{\int I(\lambda)\ r_{max}(\lambda)\ q_j(\lambda)\ d\lambda}\ , \qquad (2)$$

where $r_{max}(\lambda)$ is the reflectance spectrum for a white reflector. The α_{ij} are the components of the object-color vectors. The templates are similarly constructed with

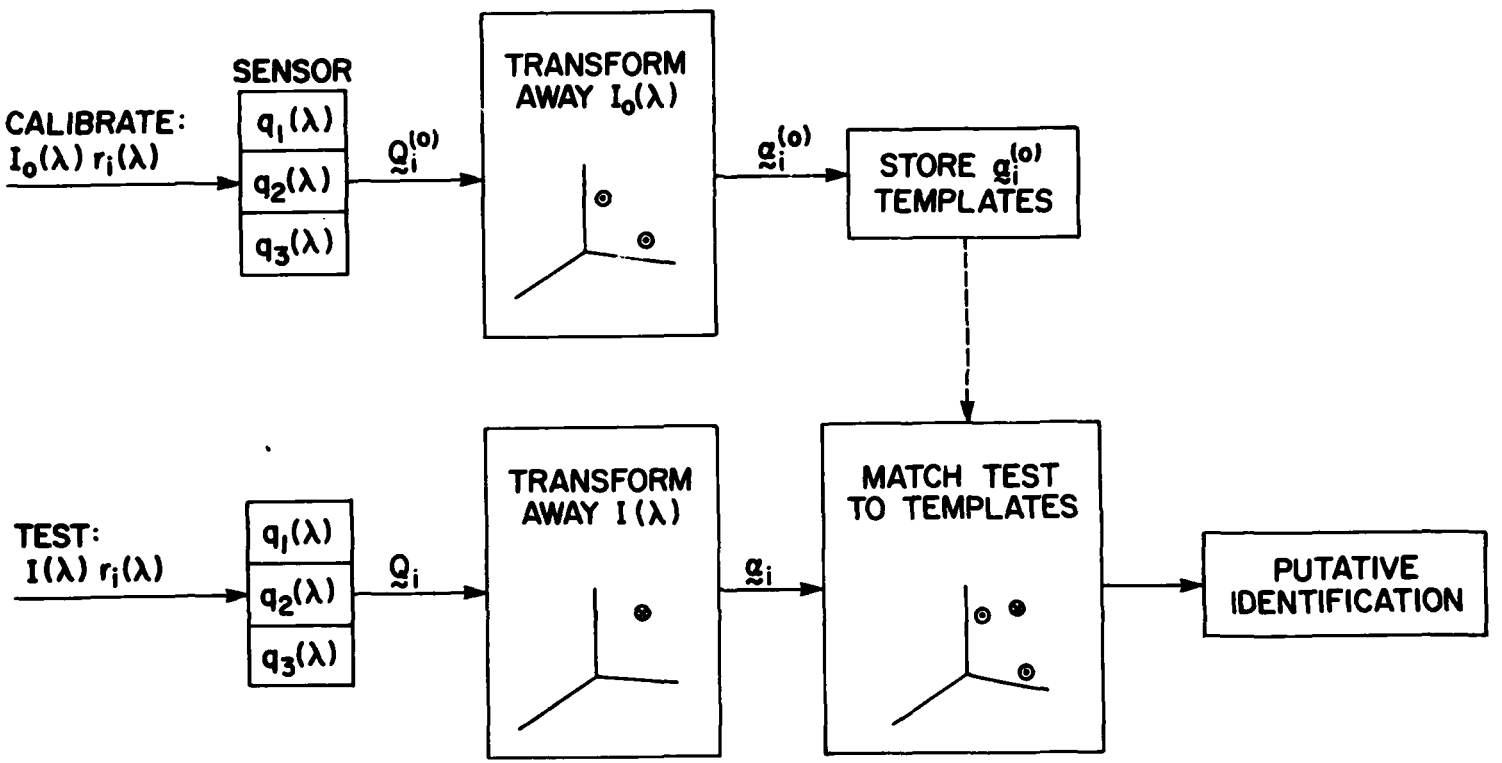

Fig. XXVIII-1. General recognizer.

$$\alpha_{ij}^{(0)} = Q_{ij}^{(0)}/Q_{j\,max}^{(0)}. \tag{3}$$

The assurance that the reference white is in the visual field and its assumed prior identification are what render our version of the Retinex theory "streamlined." Further processing to determine the identity of this reflector or a suitable substitute if it is absent from the visual field can only compromise color constancy; the "streamlined" theory has a maximum of color constancy, even though it may not agree as well as the complete theory with a more general interpretation that involves psychophysical data. Also, we note the following procedural differences from McCann et al.[3]: McCann et al. did actual spectrophotometry, whereas we obtained tabular illuminant and reflectance spectra (at 16 wavelengths) and multiplied them together to give reflected-light spectra; also, McCann et al. used Brown and Wald's[4] spectrophotometric experiments on the human eye to generate $q_j(\lambda)$, but we used Pearson and Yule's[5] choice of basis for C.I.E. tristimulus curves that are nonnegative and have minimum overlap. We did this in order to preserve metamers dictated by the C.I.E. system. (As will be seen, choice of linear combination of C.I.E. curves is immaterial to the volumetric algorithm, since volume ratios are linear-group invariants.)

Whereas in the above method a single reflector (white) was used as a reference, the volumetric method requires <u>three</u> reference reflectances. The algorithm based on the volumetric theory can be derived from the assumption that

$$r_i(\lambda) = \sum_{k=1}^{3} \alpha_{ik} u_k(\lambda), \tag{4}$$

where $u_k(\lambda)$ are the reflectances of the three reference objects. (This assumption agrees with Cohen's conclusion[6] based on a principal-components analysis on over 400 Munsell pigments.) Then

$$\int I(\lambda)\, r_i(\lambda)\, q_j(\lambda)\, d\lambda = \sum_{k=1}^{3} \alpha_{ik} \int I(\lambda)\, u_k(\lambda)\, q_j(\lambda)\, d\lambda \tag{5}$$

whence

$$Q_{ij} = \sum_{k=1}^{3} \alpha_{ik} P_{kj} \tag{6}$$

(where P_{kj} is the j^{th} tristimulus value of the k^{th} reference color). Given one tristimulus row-vector $\underline{Q}_i$ and three reference tristimulus row-vectors making square matrix [P], it follows that

$$\underline{\alpha}_i = \underline{Q}_i[P]^{-1} \tag{7}$$

is illuminant-invariant.

Each component α_{ik} is a tristimulus volume ratio. To see this, use Cramer's rule to solve $\underline{Q}_i = \underline{\alpha}_i[P]$ for $\underline{\alpha}_i$, and note that α_{ik} is a ratio of determinants (volumes):

$$\alpha_{i1} = \frac{V_{0i23}}{V_{0123}}, \qquad \alpha_{i2} = \frac{V_{01i3}}{V_{0123}}, \qquad \alpha_{i3} = \frac{V_{012i}}{V_{0123}}, \tag{8}$$

where, e.g., V_{0123} is the directed volume of the parallelepiped generated by the origin of tristimulus space and the reflected-light tristimulus points generated by the reference objects 1,2,3.

In the general schematic of Fig. XXVIII-1, the i^{th} object-color three-vector is given by $\underline{\alpha}_i = \underline{Q}_i[P]^{-1}$ and the i^{th} template is given by $\underline{\alpha}_i^{(0)} = \underline{Q}_i^{(0)}[P^{(0)}]^{-1}$. The performance of the volumetric recognizer depends on how illuminant-invariant the inferred $\underline{\alpha}_i$ actually are for real spectra.

To reiterate the principle of the recognizer, it is presumed that, ahead of time, all the objects in the universe of discourse are examined (with prior knowledge of their color names) under a light $I_0(\lambda)$. The true names of several reference colors guaranteed to appear in the visual field (three in the case of volumetric theory and one in the case of the comparison theory) are given together with their tristimulus values under a test light. Then the other object colors under this new light are putatively named by matching their object-color vectors with the templates.

The data base for the present recognizer consisted of the following.

There were 37 illuminant spectra:

a. 10 black-body radiators with T = 2000-10,000°K in 1000°K increments, and also T = ∞°K.

b. 5 Abbot-Gibson daylights, with correlated-color temperatures 4800, 5500, 6500, 7500, and 10,000°K.

c. C and A illuminants, and high-pressure sodium and mercury lights.

d. 18 fluorescent lights (spectra furnished by Dr. W. Thornton of Westinghouse Corporation).

The calibration-light spectrum was equal-energy at all wavelengths.

We used 45 artists' pigment spectra from the spectrophotometric data of Barnes.[7] All of Barnes' spectra were used except the blacks, greys, and whites, which we replaced with a spectrally nonselective 3-percent black and a 98-percent white. In all, there were 47 pigment spectra. The white was the reference color in the scaled-integrated reflectance algorithm, and for the volumetric theory we used French ultramarine blue, emerald green, and cadmium red. (These were observed to be qualitatively different from each other, but were not chosen by any quantitative means.)

The results of the simulation are shown in Table XXVIII-1. The fractions are the total number of recognition errors (incorrect template matches) divided by the

Table XXVIII-1. Error-rate results.

	Volumetric Recognizer	Scaled-Integrated Reflectance Recognizer
All lights	209/1628 = 12.2%	353/1702 = 20.7%
Nonfluorescent	57/836 = 6.8%	103/874 = 11.8%
Fluorescent	152/792 = 17.9%	249/828 = 30.1%
Sodium	14 errors	26 errors
Gold fluorescent	42 errors	36 errors

total number of recognitions. For the volumetric algorithm, the three reference object-color templates are preserved but the corresponding object-color vectors are removed from the score computation (since they are recognized perfectly by

definition). Thus the total number of putative recognitions is given by 44 object colors times 37 illuminants. Similarly, in the comparison algorithm, the reference white is eliminated as a test vector but not as a template for possible confusion. The total number of recognitions in that case is given by 46 pigments times 37 illuminants. Absolute numbers of errors are listed for worst-case illuminants in the fluorescent (gold fluorescent, used in photo-resist manufacturing) and nonfluorescent (high-pressure sodium) classes. This is done to indicate that a large number of errors came from a few illuminants that are clearly not conducive to color constancy via any theory. As expected, fluorescent lights generally gave less color constancy than nonfluorescents. Although scaled-integrated reflectance theory gives substantial color constancy as revealed by the object-color recognizer, we concluded from the results of Table XXVIII-1 that volumetric theory is more effective in producing color constancy (illuminant-invariant assessment of chromatic relations).

After presenting this work to the Optical Society of America and at SRI International, we were prompted by a question from Dr. D.H. Kelly (SRI) to consider the conditions under which the volumetric algorithm would recognize object colors seen in a television reproduction. It turns out that so long as the system has a gamma of one and the taking sensitivities of the TV camera are linear combinations of the spectral sensitivities of the recognizer (Maxwell-Ives criterion), the object-color recognizer automatically corrects for the transformation of the image between real life and TV. Equivalently (subject to the above restrictions), the algorithm corrects for transformations of the image due to photographing it through three other filters. This can be seen as follows:

Let the system taking sensitivities be

$$P_j(\lambda) = \sum_{k=1}^{3} b_{jk} q_k(\lambda). \tag{9}$$

Corresponding to the i^{th} reflector, the color separations have transmittances

$$T_{ij} = \sum_{k=1}^{3} b_{jk} \int I(\lambda)\, r_i(\lambda)\, q_k(\lambda)\, d\lambda = \sum_{k=1}^{3} b_{jk} Q_{ik}, \tag{10}$$

where Q_{ik} are the tristimulus values of the i^{th} object when it is seen directly

by the recognizer. The transmittances T_{ij} of the color separations modulate (in a spectrally nonselective way) the spectral power distributions of three light sources (or phosphors) $S_j(\lambda)$. The reprojected lights $T_{ij}S_j(\lambda)$ add together on a white screen, and are reflected back to the "eye". The tristimulus values due to the i^{th} object represented in the processed image are

$$Q_{i\ell} = \sum_{j=1}^{3} T_{ij} \int S_j(\lambda)\, q_\ell(\lambda)\, d\lambda = \sum_{j=1}^{3} \sum_{k=1}^{3} b_{jk} Q_{ik} \int S_j(\lambda)\, q_\ell(\lambda)\, d\lambda$$

$$= \sum_{k=1}^{3} \left[\sum_{j=1}^{3} b_{jk} \int S_j(\lambda)\, q_\ell(\lambda)\, d\lambda \right] Q_{ik} \equiv \sum_{k=1}^{3} C_{\ell k} Q_{ik}. \qquad (11)$$

This is an invertible linear transformation on the original tristimulus vectors, which — as has been demonstrated — is automatically compensated by the volumetric algorithm.

These findings will be the subject of two forthcoming papers.

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PUBLICATIONS AND REPORTS

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January 10-12, 1979

A.V. Oppenheim, Talk is Cheap (Invited)

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491 Thomas F. Quatieri, Jr., Phase Estimation with Application to Speech Analysis-Synthesis

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Uchikawa, Takasi (22)
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Vlannes, Nickolas P.
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Wiegner, Allen W.
Wiener, Andrew M.
Yang, Run Chan David
Yip, Moira J.

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(2) Schlumberger Fellow
(3) RLE Industrial Fellow
(4) M.I.T. Karl T. Compton Fellow
(5) NSF Fellow
(6) Bell Laboratories Fellow
(7) NIH Trainee
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(9) Quaid-E-Azem Scholarship
(10) National Consortium Fellowship
(11) Sony Corporation Fellowship
(12) Winton Hayes Fellow
(13) Belgian American Educational Foundation
(14) LNS — R.A.
(15) Japanese Society for Promotion of Science
(16) DOE Trainee
(17) Rotary Foundation Fellow
(18) L.L. Support
(19) Tel. France Scholarship
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Bowen, John P.
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Brzustowicz, Michael A.
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Carrette, George J.
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Barron, Gladys
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Fang, Li
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Fownes, Marilyn R.
Geitz, Sarah

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Thompson, Joy C.

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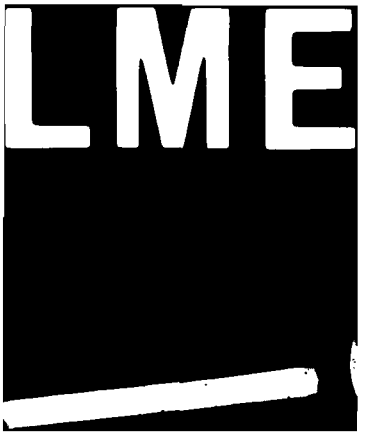
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